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Klemen et al.

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(45) **Date of Patent: May 25, 2021**

(54) **CONTROL OF LOW PRESSURE GENERATOR FOR GAS TURBINE ENGINE**

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(51) **Int. Cl.**

F01D 15/10 (2006.01)
F02C 7/32 (2006.01)
(Continued)

(52) **U.S. Cl.**

CPC .... ***B60R 16/03*** (2013.01); ***B64D 27/10*** (2013.01); ***F01D 15/10*** (2013.01); ***F01D 17/02*** (2013.01); ***F01D 17/24*** (2013.01); ***F02C 3/04*** (2013.01); ***F02C 3/10*** (2013.01); ***F02C 7/06*** (2013.01); ***F02C 7/275*** (2013.01); ***F02C 7/32*** (2013.01); ***F02C 7/36*** (2013.01); ***F02K 3/06*** (2013.01); ***H02K 5/1732*** (2013.01); (Continued)

(58) **Field of Classification Search**

CPC B64D 2027/026; F01D 15/10; F02K 3/06
See application file for complete search history.

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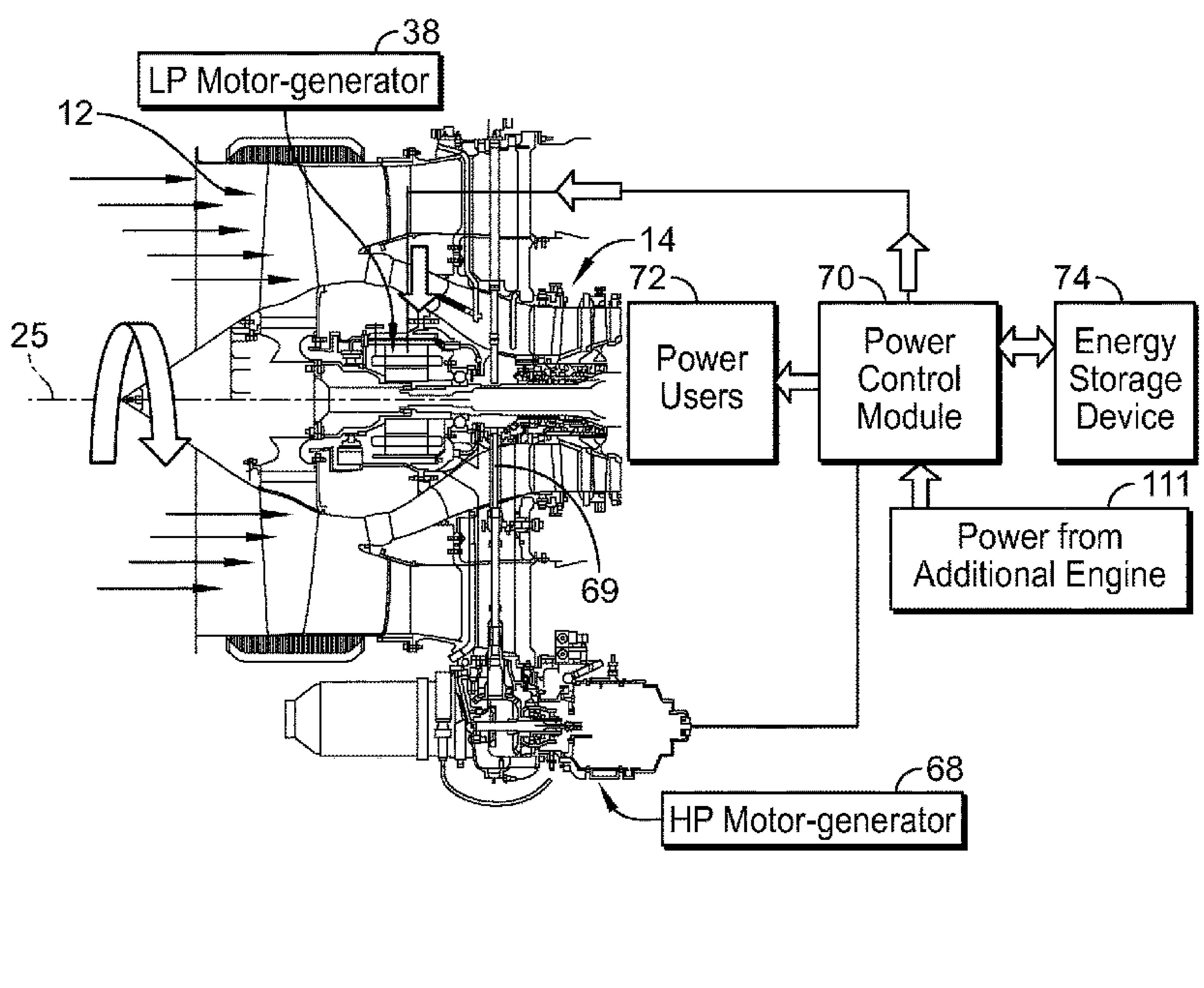
(57) **ABSTRACT**

A turbofan gas turbine engine includes low pressure (LP) motor-generator operable in either a generation mode or a drive mode, an high pressure (HP) motor-generator operable in a either a generation mode or a drive mode, and a power control module for selectively operating the LP and HP motor-generators according to operational conditions of the engine.

9 Claims, 10 Drawing Sheets



Related U.S. Application Data

filed on May 18, 2016, provisional application No. 62/338,205, filed on May 18, 2016, provisional application No. 62/433,576, filed on Dec. 13, 2016.

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F02C 3/10	(2006.01)
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F02C 3/04	(2006.01)
F02C 7/06	(2006.01)
F02C 7/275	(2006.01)
F02C 7/36	(2006.01)
F01D 17/02	(2006.01)
F01D 17/24	(2006.01)
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H02K 5/173	(2006.01)
H02K 9/19	(2006.01)
B64D 27/10	(2006.01)
H02P 9/04	(2006.01)

(52) **U.S. Cl.**

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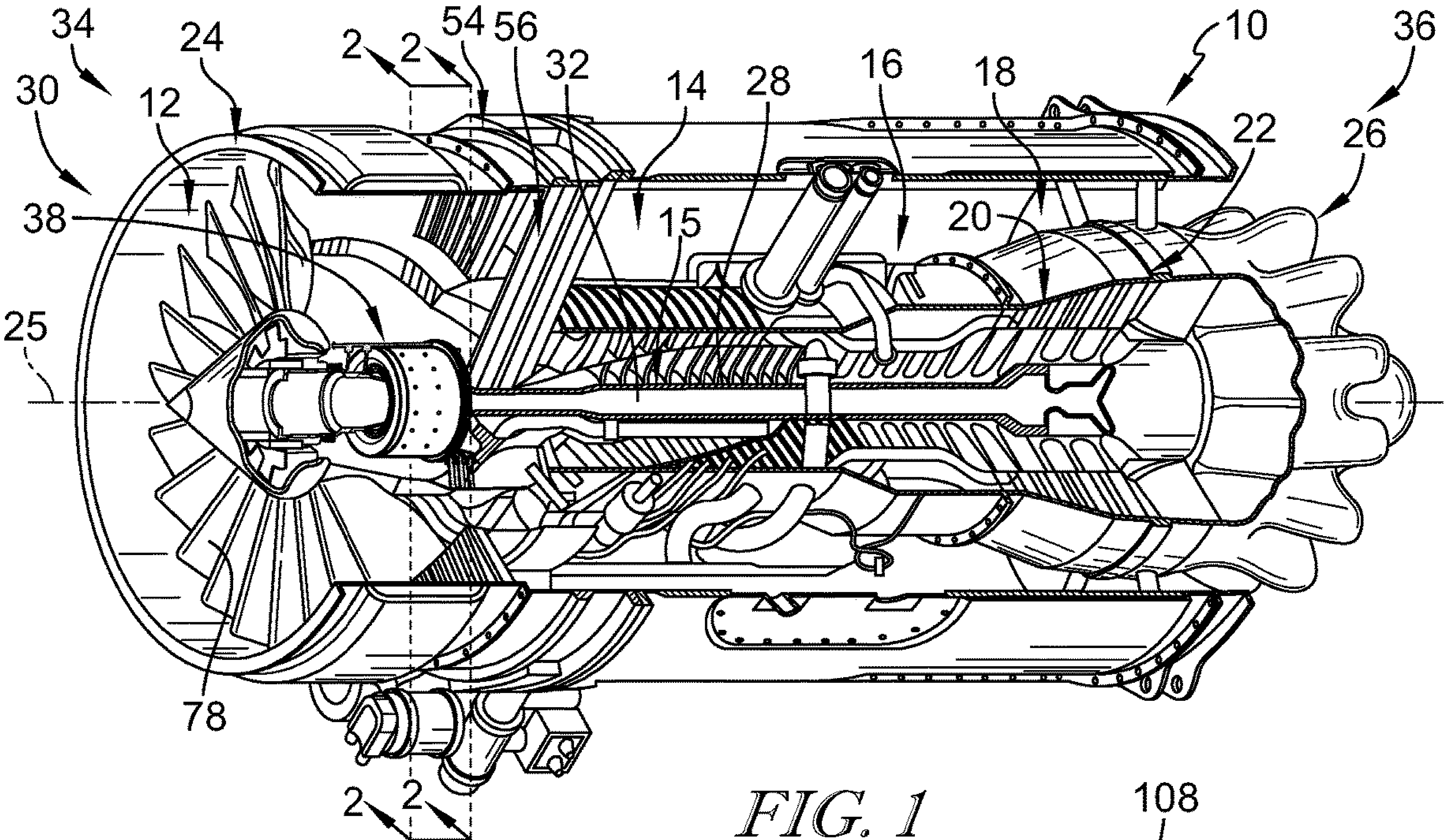
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FIG. 1

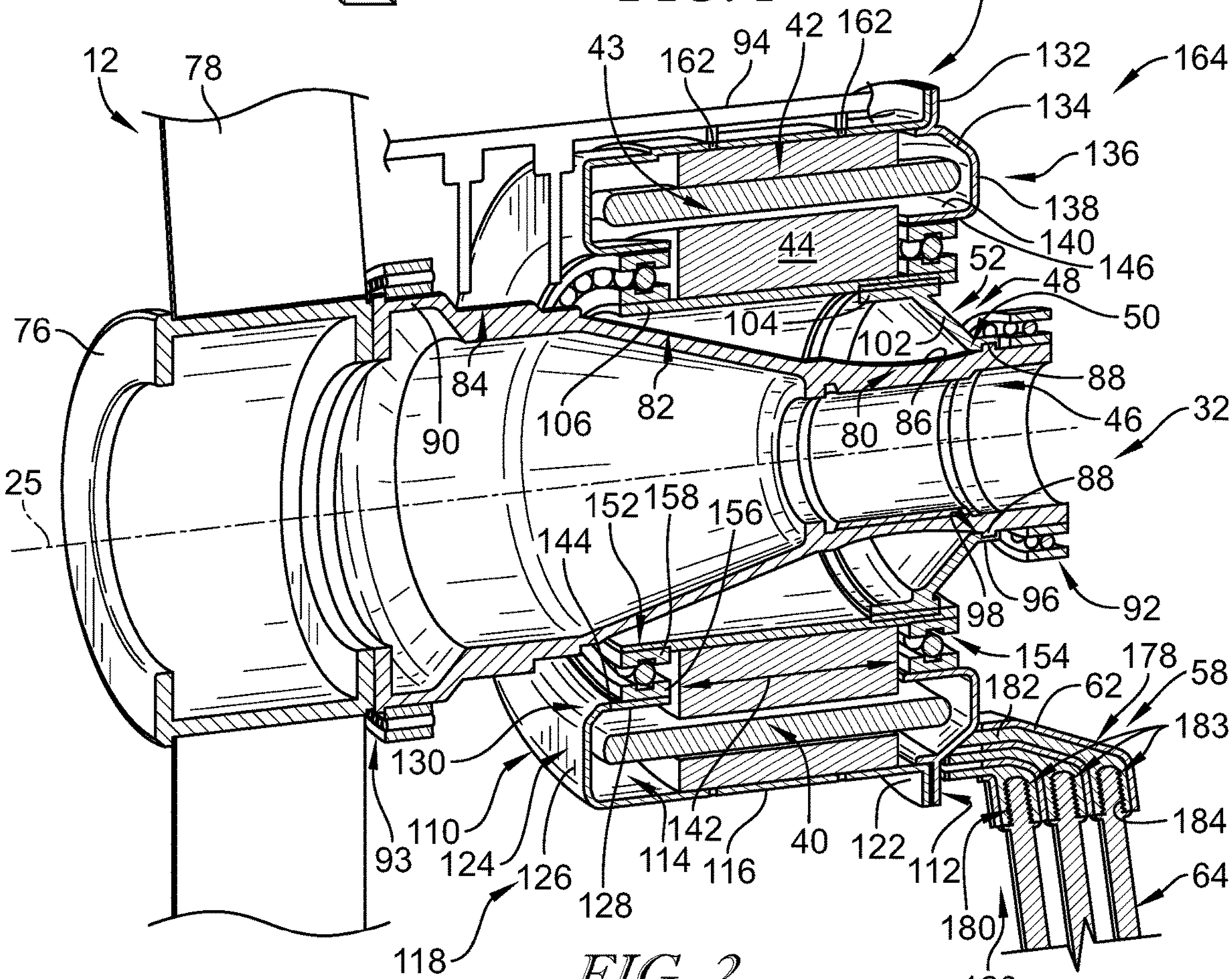
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FIG. 2

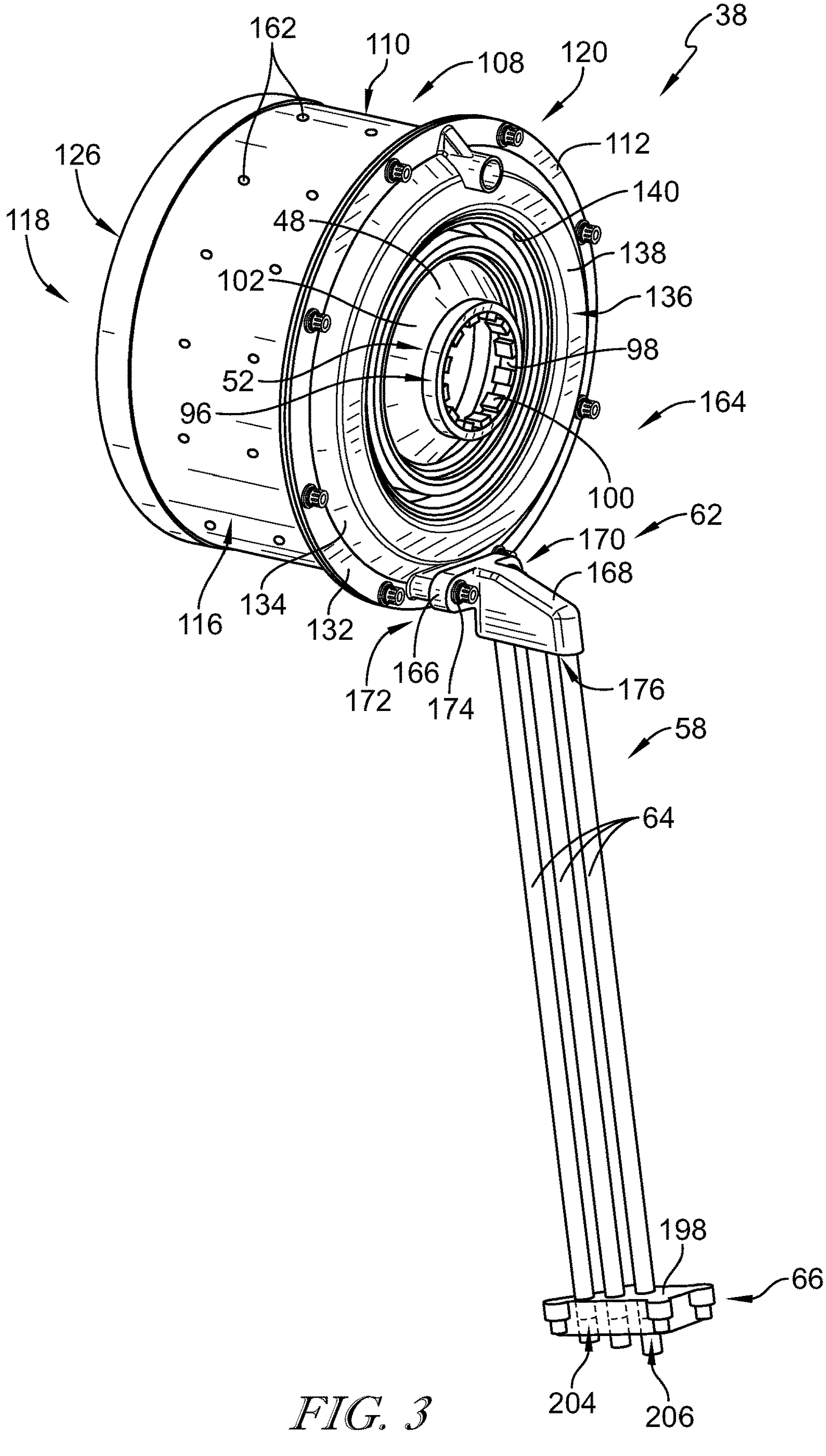
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FIG. 3

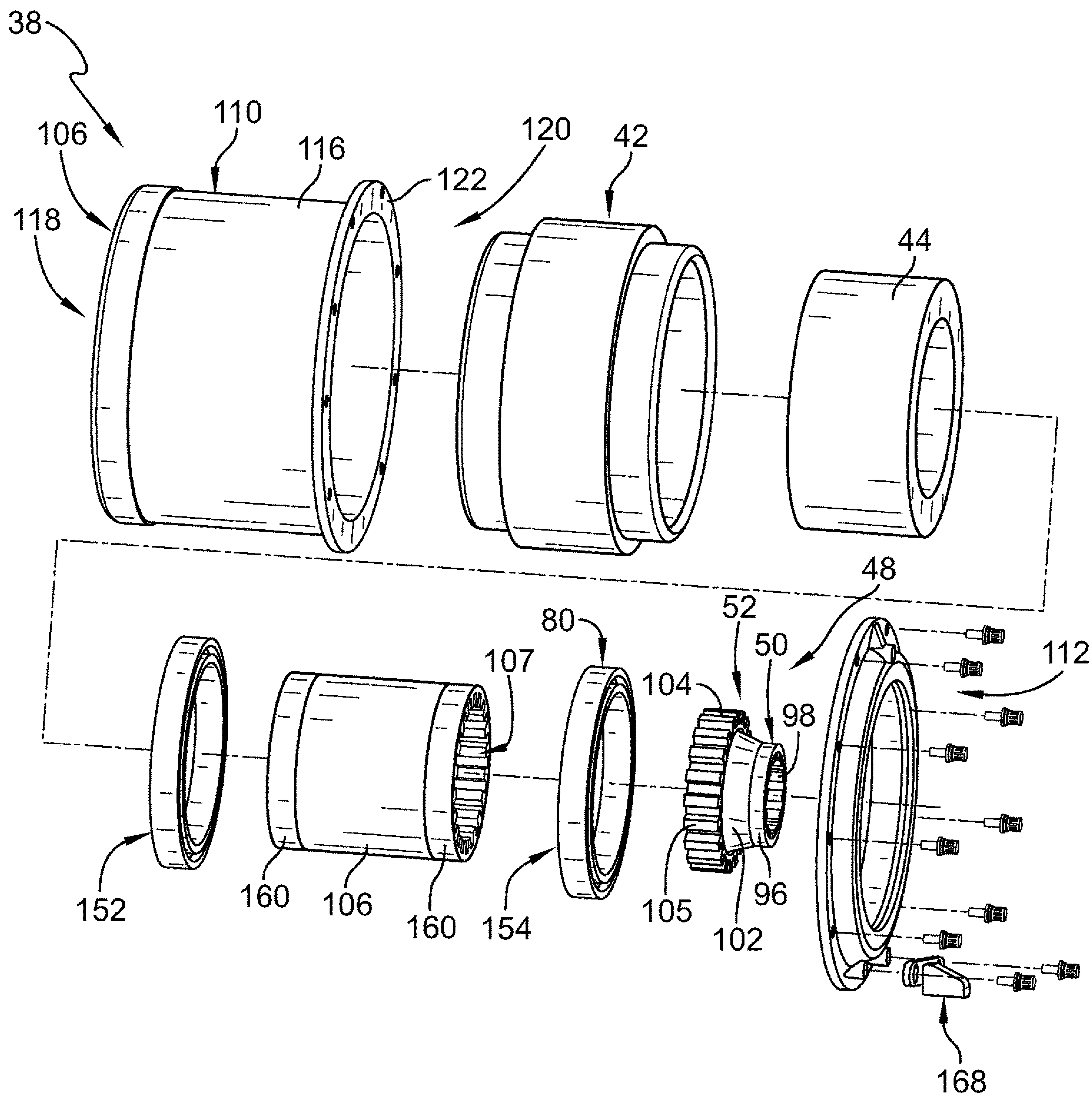
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FIG. 4

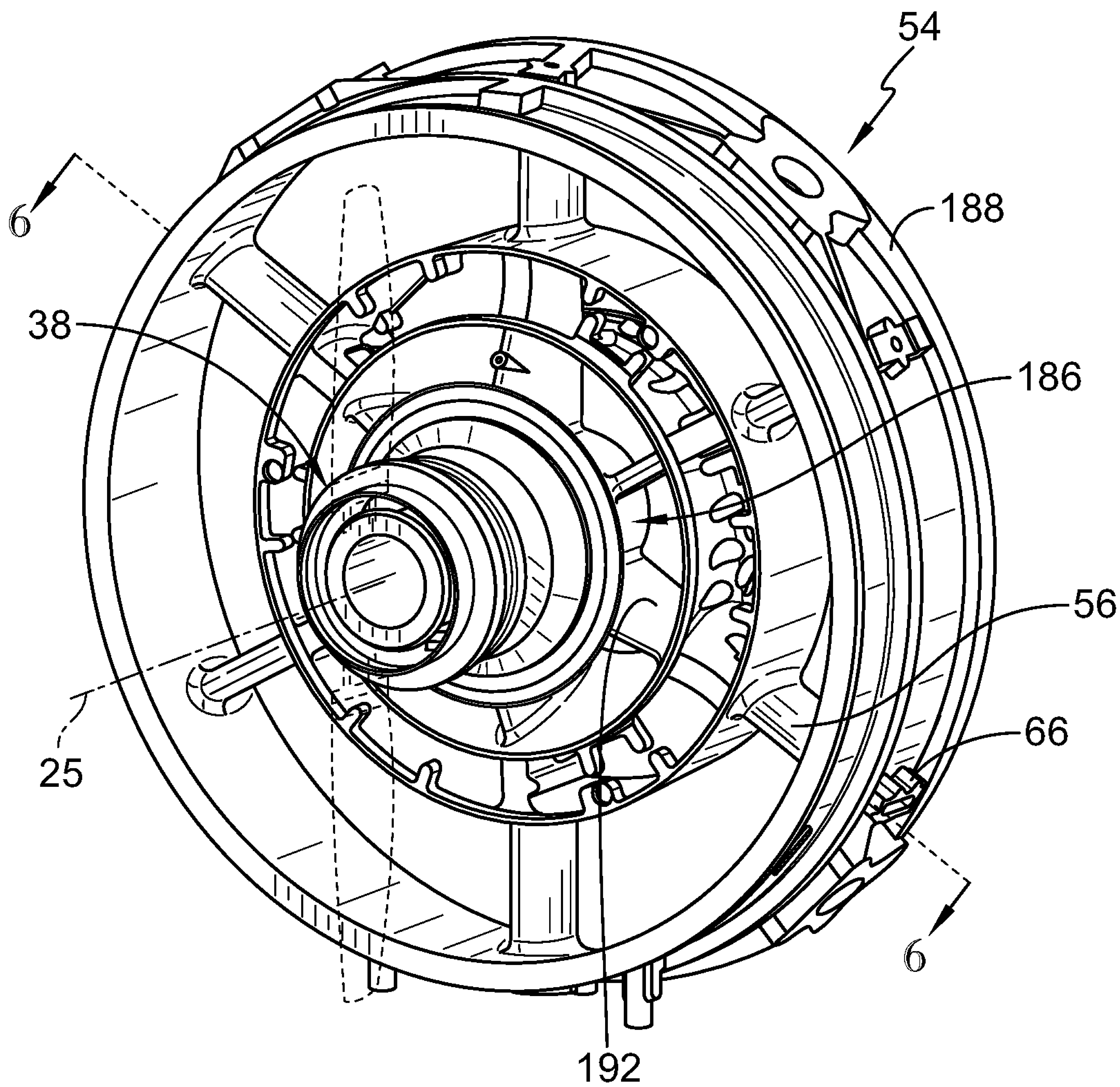

FIG. 5

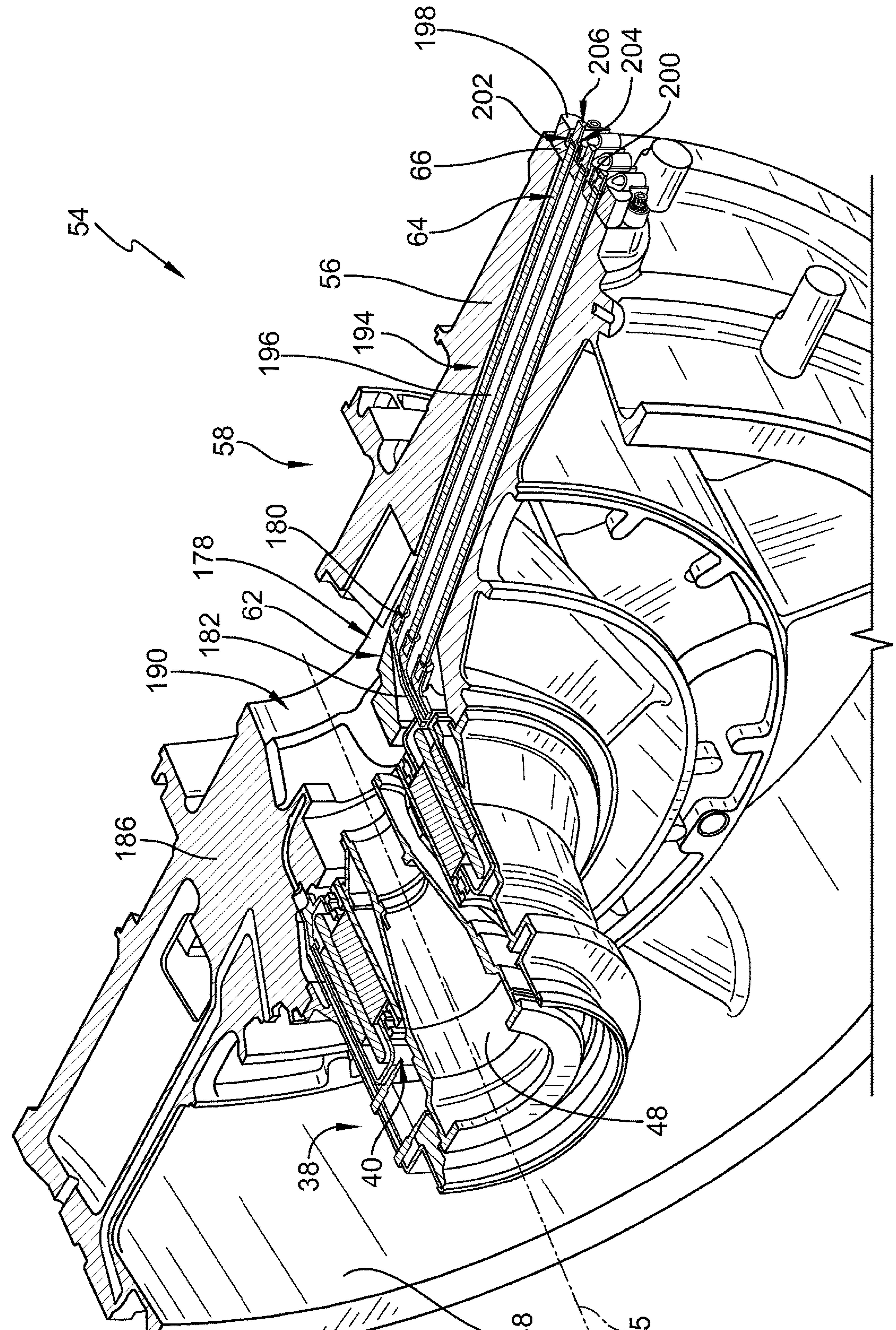
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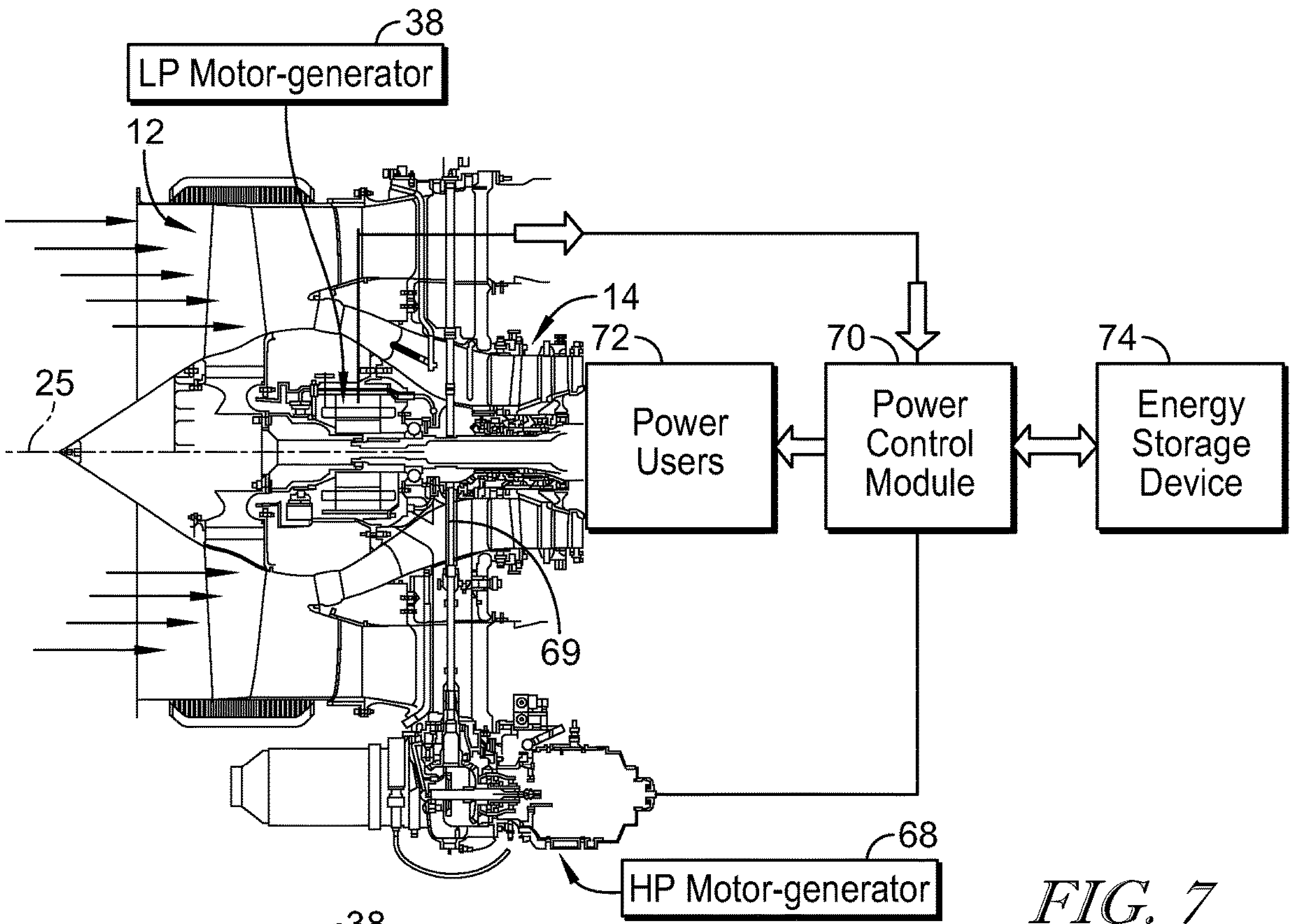
FIG. 6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LP Motor-generator
12
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74
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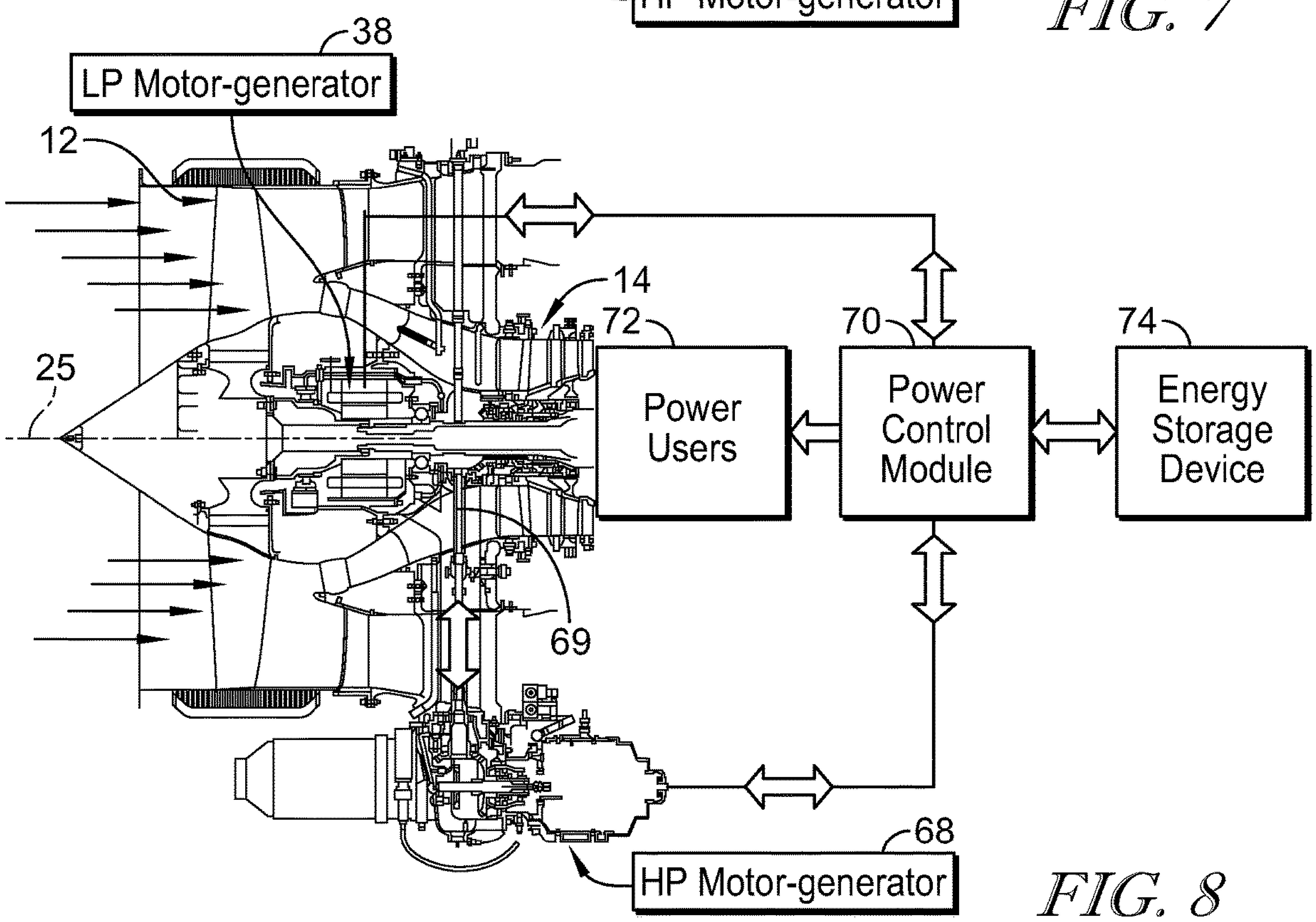
Power Users
Power Control Module
Energy Storage Device
69
68
HP Motor-generator

FIG. 7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14
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25
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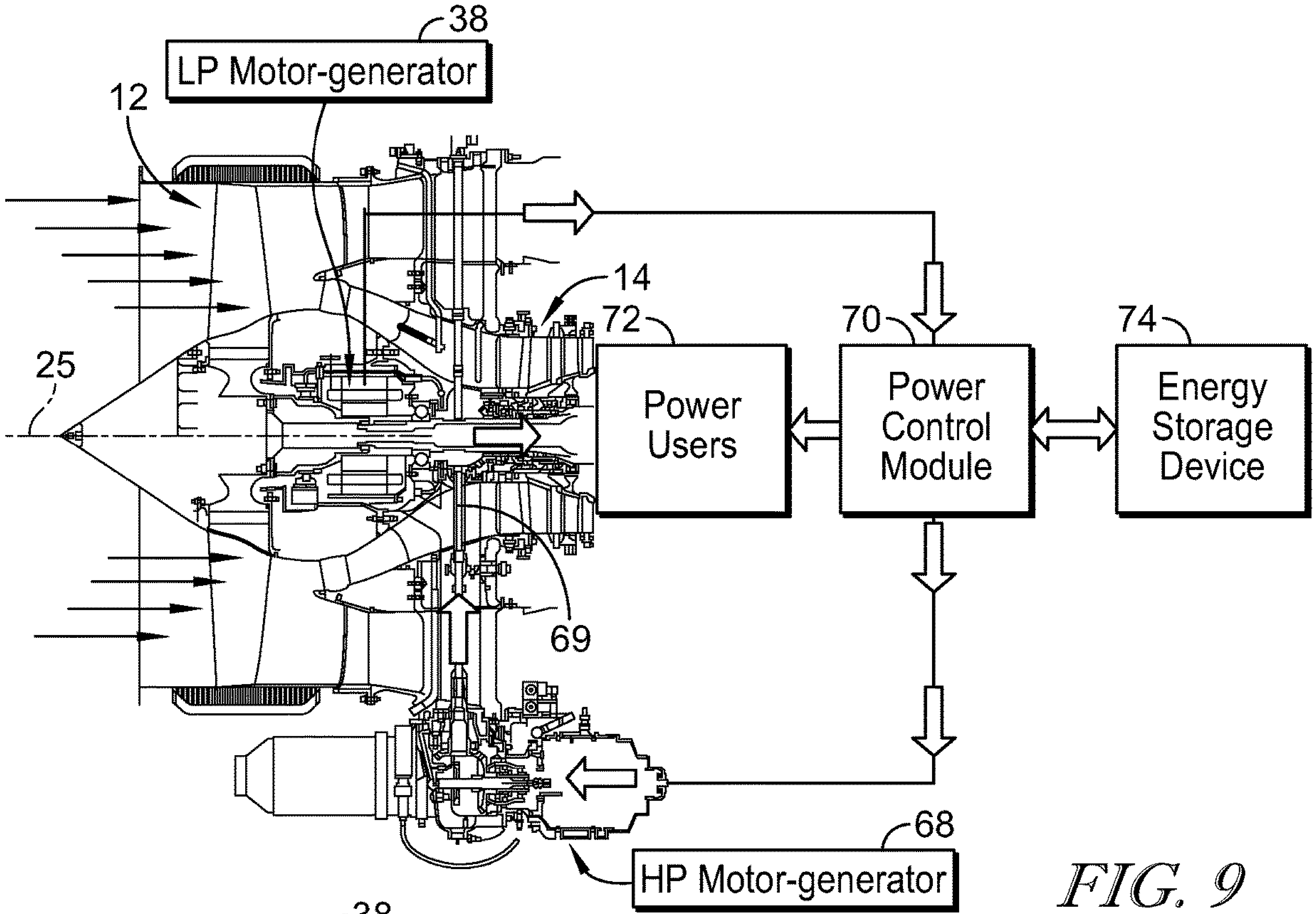
Power Control Module
Energy Storage Device
69
68
HP Motor-generator

FIG. 8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14
72
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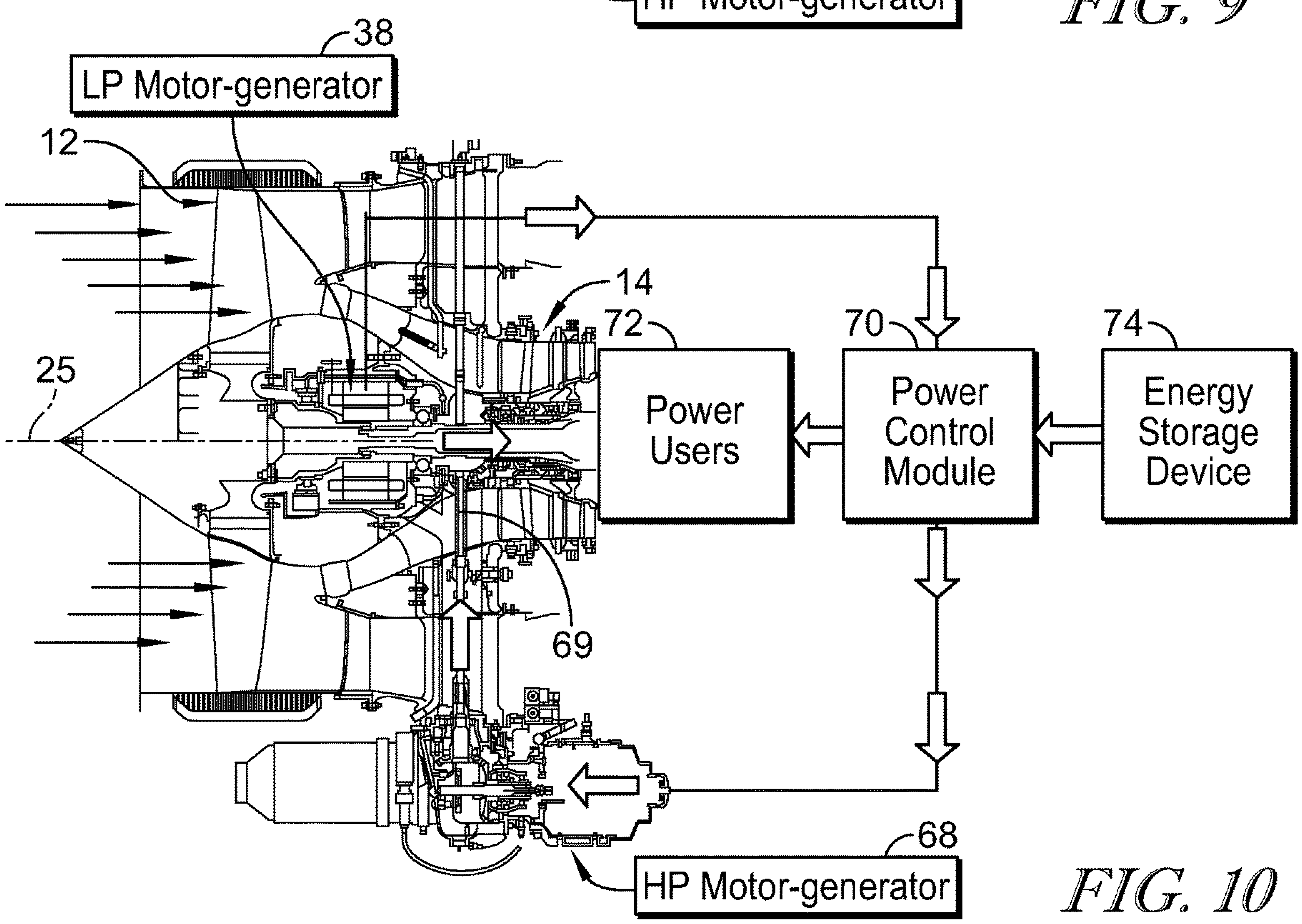
Power Users
Power Control Module
Energy Storage Device
69
68
HP Motor-generator

FIG. 9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12
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Power Control Module
Energy Storage Device
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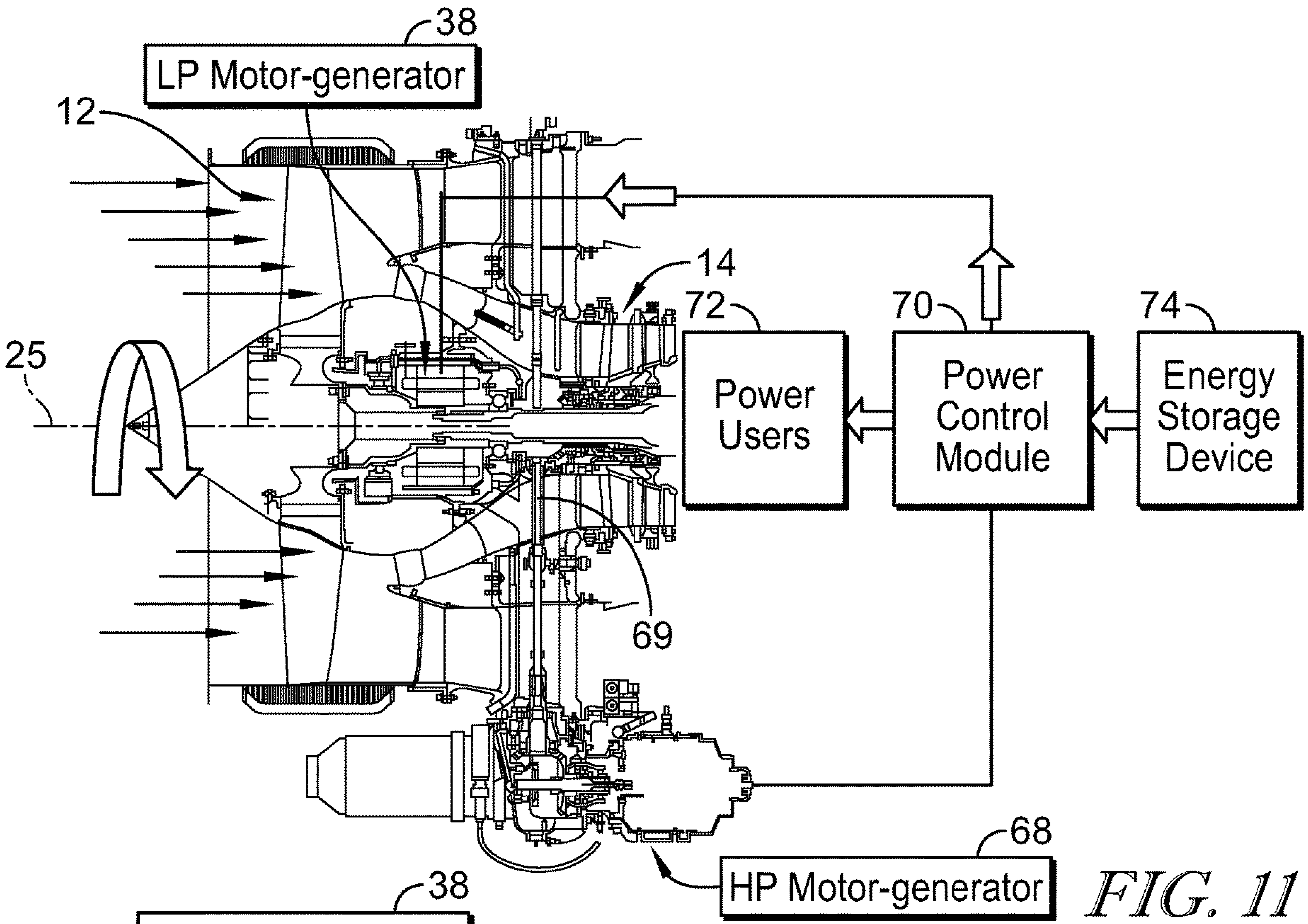
HP Motor-generator

FIG. 10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12
14
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72
Power Users
70
Power Control Module
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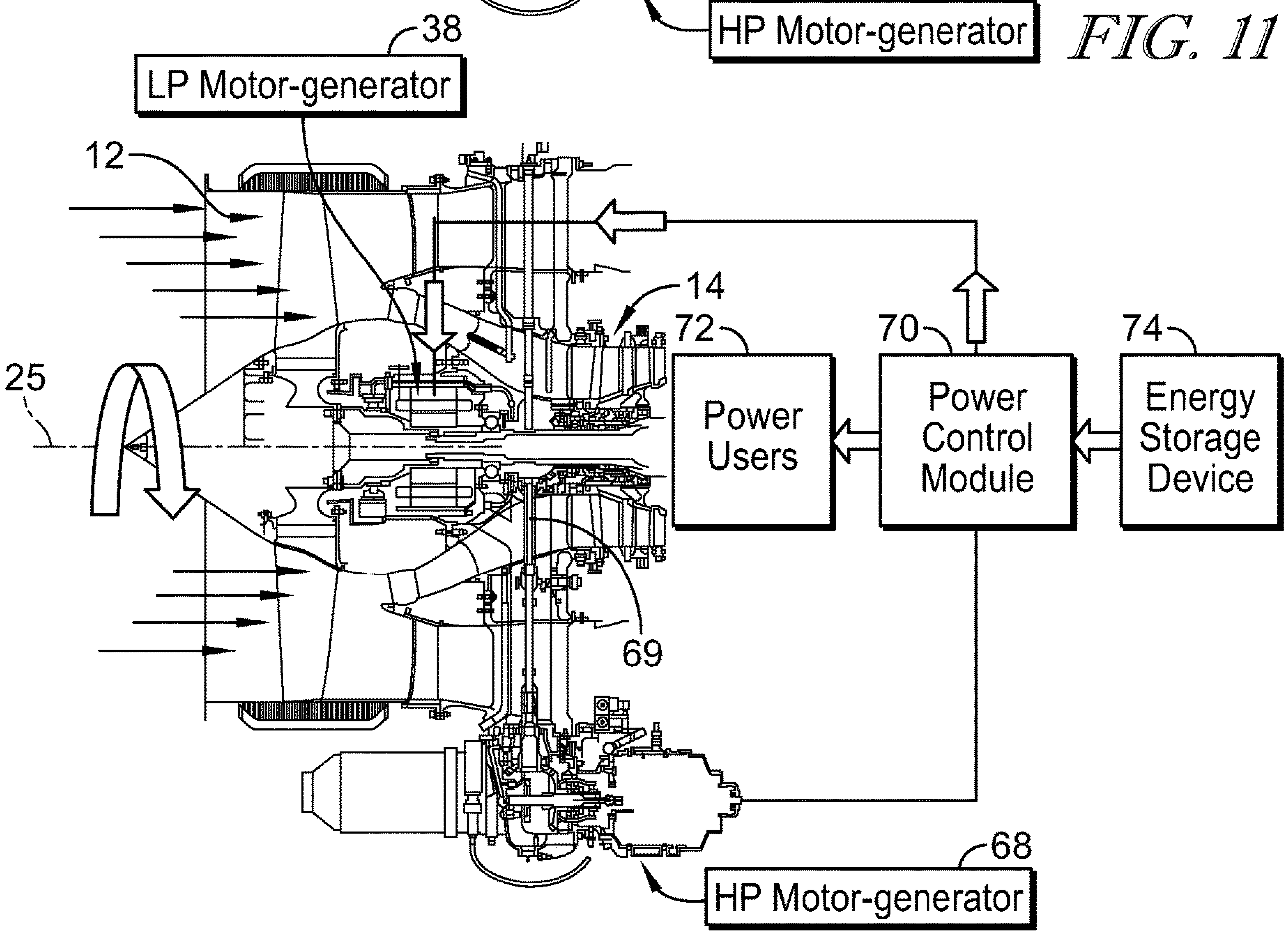
Energy Storage Device
69
68
HP Motor-generator

FIG. 11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12
14
25
72
Power Users
70
Power Control Module
74
Energy Storage Device
69
68
HP Motor-generator

FIG. 12

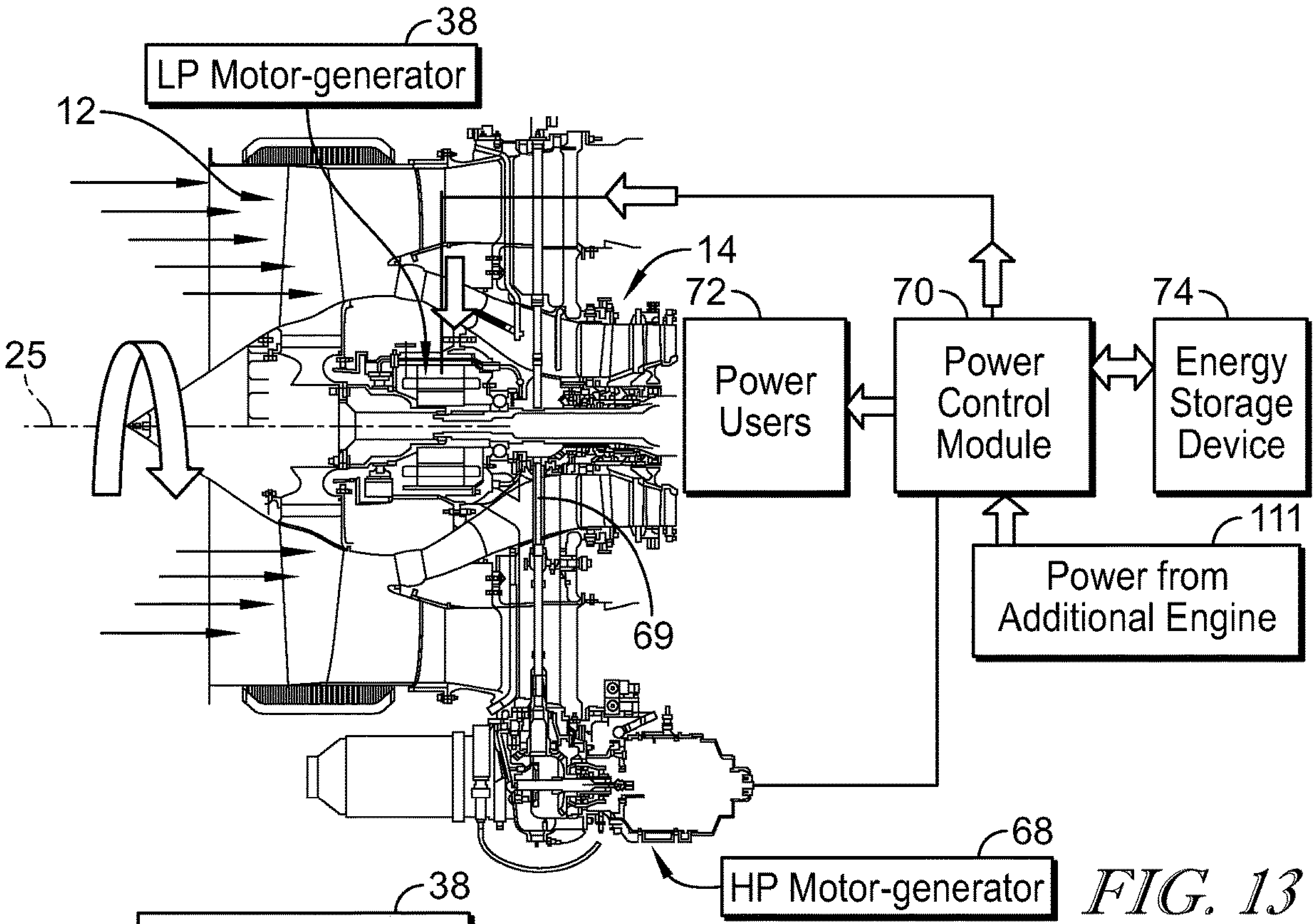
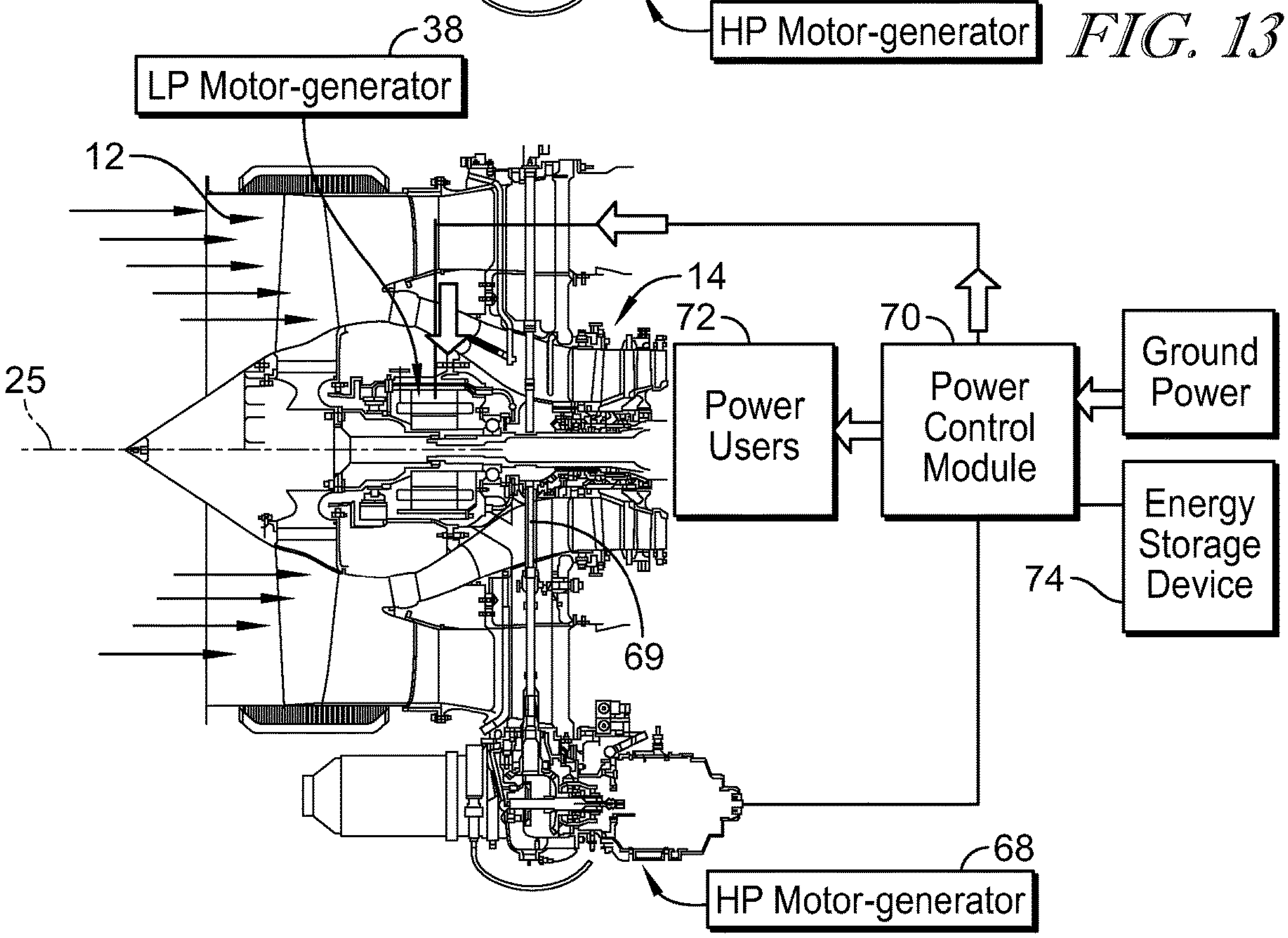

38
LP Motor-generator
12
14
25
72
Power Users
70
Power Control Module
74
Energy Storage Device
111
Power from Additional Engine
69
68
HP Motor-generator

FIG. 13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LP Motor-generator
12
14
25
72
Power Users
70
Power Control Module
Ground Power
Energy Storage Device
74
69
68
HP Motor-generator

FIG. 14

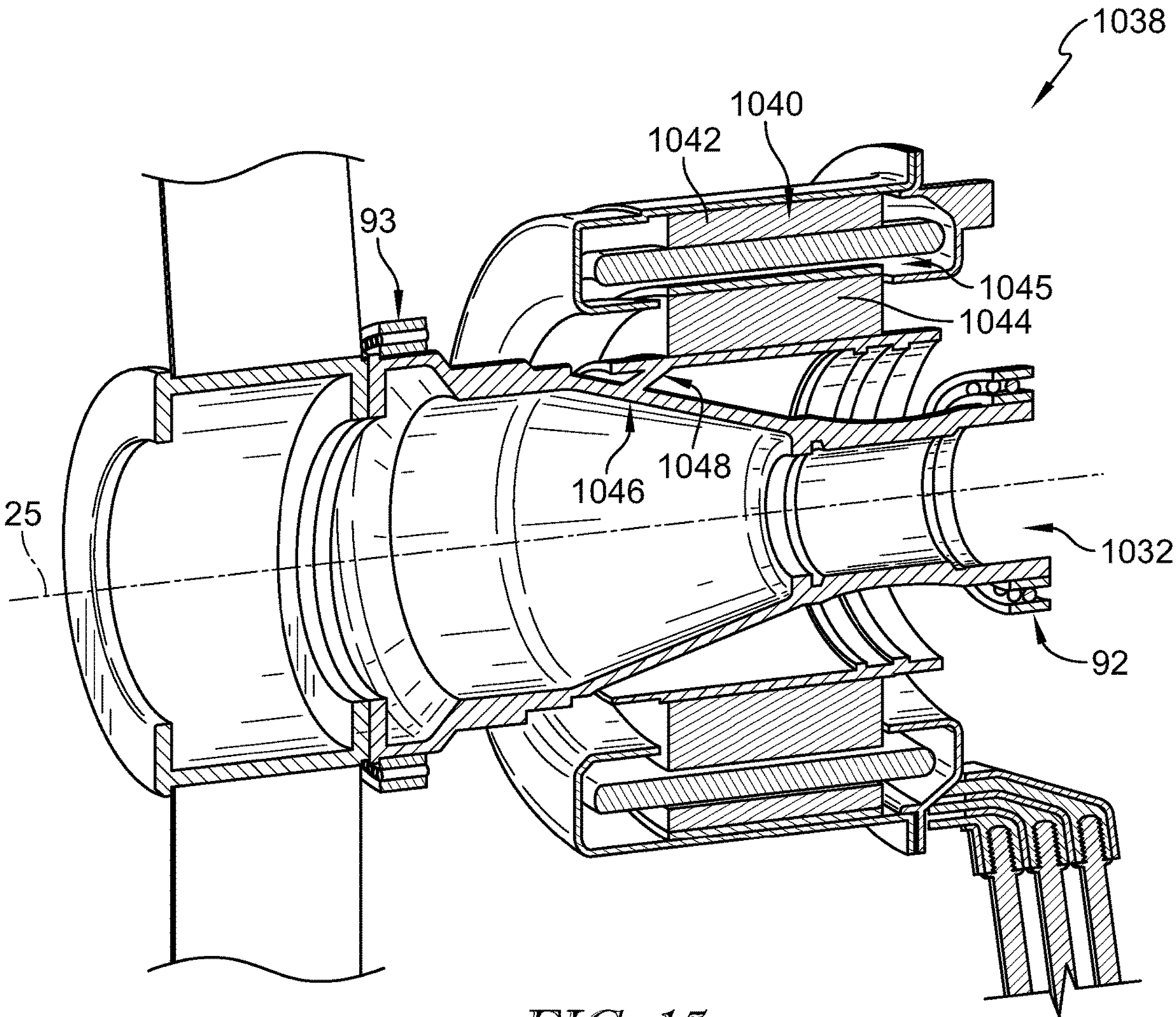

FIG. 15

CONTROL OF LOW PRESSURE GENERATOR FOR GAS TURBINE ENGINE

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to and the benefit of U.S. Provisional Patent Application Nos. 62/338,201, filed 18 May 2016; 62/338,204, filed 18 May 2016; 62/338,205, filed 18 May 2016; and 62/433,576, filed 13 Dec. 2016, the disclosures of which are now expressly incorporated herein by reference.

FIELD OF THE DISCLOSURE

The present disclosure relates generally to gas turbine engines, and more specifically to auxiliary electric power generators of gas turbine engines.

BACKGROUND

Gas turbine engines are used to power aircraft, watercraft, electrical generators, and the like. Gas turbine engines typically include a compressor, a combustor, and a turbine. The compressor compresses air drawn into the engine and delivers high pressure air to the combustor. In the combustor, fuel is mixed with the high pressure air and is ignited. Exhaust products of the combustion reaction in the combustor are directed into the turbine where work is extracted to drive the compressor and, sometimes, an output shaft, fan, or propeller. Portions of the work extracted from the turbine can be used to drive various subsystems such as generators.

SUMMARY

The present disclosure may comprise one or more of the following features and combinations thereof.

According to an aspect of the present disclosure, a turbofan gas turbine engine may include a low pressure spool including a fan rotor, a low pressure turbine rotor, a low pressure drive shaft extending along an axis and rotationally coupling the fan rotor to receive driven rotation about the axis from the low pressure turbine rotor, and a low pressure motor-generator mounted on the low pressure drive shaft and adapted for selective operation between a generation mode to generate electric power from driven rotation of the low pressure turbine rotor and a drive mode to electrically drive rotation of the low pressure drive shaft, a high pressure spool including a compressor rotor, a high pressure turbine rotor, a high pressure drive shaft extending along the axis and rotationally coupling the compressor rotor to receive driven rotation about the axis from the high pressure turbine rotor, and an high pressure motor-generator adapted for selective operation between a generation mode to generate electric power from driven rotation of the high pressure turbine rotor and a drive mode to electrically drive rotation of the high pressure drive shaft, and a power control module electrically connected to each of the low pressure motor-generator and the high pressure motor-generator and configured to determine operational conditions of the engine and to selectively operate each of the low pressure motor-generator and the high pressure motor-generator in either of the generation mode and the drive mode based on the determined operational conditions of the engine.

In some embodiments, in response to determination that the operational conditions are steady state operational conditions, the power control module may be configured to operate the low pressure motor-generator in the generation mode under.

In some embodiments, in response to determination that the operational conditions include an efficiency of the high pressure spool that is below a predetermined threshold, the power control module may be configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist rotation of the high pressure drive shaft.

In some embodiments, the predetermined threshold may be a predetermined fuel efficiency of the high pressure spool.

In some embodiments, in response to determination that the operational conditions include an efficiency of the low pressure spool that is below a predetermined threshold, the power control module may be configured to operate the high pressure motor-generator in the generation mode and to operate the low pressure motor-generator in the drive mode to assist rotation of the low pressure drive shaft.

In some embodiments, in response to determination that the operational conditions are high demand operational conditions, the power control module is configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist the rotation of the high pressure drive shaft.

In some embodiments, high demand operational conditions may include determination that a compressor surge margin is below a predetermined threshold value.

In some embodiments, the turbofan gas turbine engine may be adapted for use in an aircraft and high demand operational conditions include determination that a flight altitude is above a predetermined threshold value.

In some embodiments, high demand operational conditions may include determination of a disruption of rotation of the fan rotor.

In some embodiments, the engine may be adapted for use in an aircraft and, in response to determination that the operational conditions include in-flight restart, the power control module is configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist restart of the engine.

In some embodiments, in response to determination that the operational conditions include loss of engine power, the power control module may be configured to selectively operate the low pressure motor-generator in the drive mode to provide thrust assist.

In some embodiments, the turbofan gas turbine engine may include an energy storage device electrically connected to the power control module to selectively communicate electric power with the power control module.

According to another aspect of the disclosure, a method of operating a turbofan gas turbine engine of an aircraft having a low pressure spool and a high pressure spool may include determining operational conditions of the aircraft, selectively operating a low pressure motor-generator of the low pressure spool between a generation mode to generate electric power from driven rotation of a low pressure turbine rotor of the low pressure spool and a drive mode to electrically drive rotation of a low pressure drive shaft of the low pressure spool based on the determined operational conditions of the aircraft, and selectively operating a high pressure motor-generator of the high pressure spool between a generation mode to generate electric power from driven rotation of an high pressure turbine rotor of the high pressure spool and a drive mode to electrically drive rotation of a high pressure drive shaft of the high pressure spool based on the determined operational conditions of the aircraft.

In some embodiments, selectively operating the low pressure motor-generator may include, in response to determination that operational conditions are steady state, operating the low pressure motor-generator in the generation mode.

In some embodiments, selectively operating the low pressure motor-generator and selectively operating the high pressure motor-generator respectively may include, in response to determination that the operational conditions include an efficiency of the high pressure spool that is below a predetermined threshold, operating the low pressure motor-generator in the generation mode and operating the high pressure motor-generator in the drive mode, to assist rotation of the high pressure drive shaft.

In some embodiments, the predetermined threshold may be a predetermined fuel efficiency of the high pressure spool.

In some embodiments, selectively operating the high pressure motor-generator and selectively operating the low pressure motor-generator respectively may include, in response to a determination that operational conditions include an efficiency of the low pressure turbine section is below a predetermined threshold, operating the high pressure motor-generator in the generation mode, and operating the low pressure motor-generator in the drive mode, to assist rotation of the low pressure drive shaft.

In some embodiments, selectively operating the high pressure motor-generator and selectively operating the low pressure motor-generator respectively may include, in response to a determination that the operational conditions include high demand conditions, operating the high pressure motor-generator in the drive mode to assist rotation of the high pressure drive shaft, and operating the low pressure motor-generator in the generation mode to supply electric power to the high pressure motor-generator.

In some embodiments, the high demand conditions may include compressor surge margin being below a threshold value.

In some embodiments, the high demand conditions may include flight altitude being above a predetermined threshold value.

In some embodiments, the method may include selectively storing electric power from one of the low pressure motor-generator and the high pressure motor-generator in an energy storage device based on the determined operational conditions of the aircraft.

These and other features of the present disclosure will become more apparent from the following description of the illustrative embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an illustrative embodiment of a turbofan gas turbine engine with a portion cut away to show that the gas turbine engine includes a low pressure turbine spool and a high pressure spool, and showing that the low pressure spool includes a fan disposed on a forward end of the engine, a low pressure turbine rotor disposed on an aft end of the engine, and a low pressure drive shaft that extends along an axis between the forward and aft ends and is connected to each of the fan rotor and the low pressure turbine rotor to transfer rotational drive from the lower pressure turbine rotor to the fan, and showing that the high pressure spool includes a compressor, a high pressure turbine rotor, and a high pressure drive shaft that extends concentrically with the low pressure drive shaft and is connected to each of the high pressure turbine rotor and the compressor to transfer rotational drive from the high pressure turbine rotor to the compressor, and showing that the engine includes a low pressure electric motor-generator that is positioned between the fan and the compressor along the axis and is rotationally coupled to the low pressure drive shaft for selective operation as a generator to generate electric power from rotation of the low pressure drive shaft or as an electric motor to assist rotation of the low pressure drive shaft;

FIG. **2** is a perspective view of a portion of the turbofan gas turbine engine of FIG. **1** in cross-section taken along the cross-sectional plane **2-2** showing that the low pressure drive shaft includes a fan shaft and a quill shaft that is rotationally coupled to the fan shaft by a quill connection that allows movement of the fan shaft relative to the quill shaft while transferring rotational drive, and showing that the low pressure motor-generator includes a generator core having a rotor rotationally coupled with the quill shaft and a stator arranged outside of the rotor and fixed against rotation relative to the rotor, and showing that the low pressure motor-generator includes a generator housing positioned radially outside of the quill shaft and bearings disposed radially between the generator housing and the quill shaft, and a number of coolant pathways for distributing lubricant to the low pressure motor-generator;

FIG. **3** is a perspective view of the low pressure motor-generator of FIG. **2** showing that the generator housing includes a can receptacle and a cover attached to the aft end of the can receptacle, and showing that the turbofan gas turbine engine includes an electrical assembly connected to the cover of generator housing and extending radially outward from the low pressure motor-generator for connection with other loads;

FIG. **4** is an exploded perspective view of the low pressure motor generator of FIGS. **2** and **3** showing that the generator housing includes an interior cavity for housing the low pressure motor-generator core and a shaft opening therethrough for receiving the low pressure drive shaft, and showing that the quill shaft includes splines extending inwardly to form the quill connection with the fan shaft;

FIG. **5** is a perspective view of a support frame of the turbofan gas turbine engine of FIG. **1** showing that the support frame includes a number of struts extending radially to connect with a number of support collars of the support frame, and showing that the low pressure motor-generator is positioned between the fan and the support frame along the axis;

FIG. **6** is a perspective cross-sectional view of the support frame of FIG. **6** taken along the line **6-6** and showing that the electrical assembly of the LP motor-generator includes a connector electrically connected to the stator and attached to the housing of the low pressure motor-generator, a terminal base attached to an outer collar of the support frame, and a number of busbars that extend between and connect to each of the connector and the terminal base, and showing that the busbars extend radially through one of the struts to electrically connect the connector to the terminal base;

FIG. **7** is a partially diagrammatic view of the turbofan gas turbine engine of FIG. **1** showing that the engine includes a high pressure motor-generator adapted to be driven for rotation by the high pressure drive shaft, and showing that the engine includes a power control module that is electrically connected to each of the low pressure motor-generator and the high pressure motor-generator and is arranged for selectively operating each of the low pressure and high pressure motor-generators independently between the generation modes and the drive modes, and showing that the power control module is connected to communicate electrical power with an optional energy storage device, and showing by example that the power control module determines that steady state operational conditions exist, and in response to steady state conditions, the power control module operates the low pressure motor-generator in the generation mode and distributes electrical power generated by the low pressure motor-generator to an electrical user and selectively exchanges electrical power with the energy storage device;

FIG. **8** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7** showing by example that the power control module can exchange power between low pressure motor-generator and high pressure motor-generator to adjust loads applied to low pressure and high pressure spools in order to improve engine efficiency;

FIG. **9** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1**, **7**, and **8** showing by example that the power control module determines that high demand operational conditions exist and in response the power control module operates the low pressure motor-generator in the generation mode and operates the high pressure motor-generator in the drive mode to assist rotation of the high pressure drive shaft and reduce load on the high pressure spool, and showing that the power control module selectively exchanges electrical power with the energy storage device;

FIG. **10** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7-9** showing by example that the power control module determines that in-flight restart operational conditions exist and in, the power control module operates the low pressure motor-generator in the generation mode and operates the high pressure motor-generator in the drive mode to assist in-flight restart of the engine, and showing that the power control module receives electrical power from the energy storage device;

FIG. **11** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7-10** showing by example that the power control module determines that loss of engine power operational conditions exist and in response, the power control module selectively operates the low pressure motor-generator in the drive mode to provide thrust assist;

FIG. **12** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7-11** showing by example that the power control module determines that hot engine off operational conditions exist in which the engine is desirably shut down but remains at relatively high temperature and in response the power control module operates the low pressure motor-generator in the drive mode to provide electrically driven rotation of the fan to provide air to the engine for cooling engine components and expelling fumes;

FIG. **13** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7-12** showing that the power control module is electrically connected to a second high pressure motor-generator of a second gas turbine engine for individual selective operation between generation and drive modes to permit selective distribution of power between the engine and the second engine, and showing by example that the power control module determines that operational conditions do not meet threshold efficiencies, and in response to determination that operational conditions do not meet a threshold efficiency of the low pressure spool of the engine, the power control module receives electric power from the second engine and operates the low pressure motor-generator in the drive mode;

FIG. **14** is a partially diagrammatic view of the turbofan gas turbine engine of FIGS. **1** and **7-13** showing that the power control module is electrically connected to ground power source and determines that cool engine off operational conditions exist in which the engine is desirably shut down and remains at relatively cool temperature and in the power control module operates the low pressure motor-generator in the drive mode to inhibit rotation of the fan rotor to prevent rotation of the engine; and

FIG. **15** is a perspective view of a cross-section of another illustrative embodiment of the low pressure electric motor-generator of the turbofan gas turbine engine of FIG. **1** taken along the plane **2-2** and showing that the low pressure drive shaft includes a fan shaft and a quill shaft that is rotationally coupled to the fan shaft and extends from the fan shaft to rotationally connect the fan shaft and the rotor of the low pressure motor-generator for rotation.

DETAILED DESCRIPTION OF THE DRAWINGS

For the purposes of promoting an understanding of the principles of the disclosure, reference will now be made to a number of illustrative embodiments illustrated in the drawings and specific language will be used to describe the same.

Gas turbine engines may be adapted for various uses, such as to propel aircraft, watercraft, and/or for power generation. The electrical power demands on gas turbine engines adapted for such uses are rapidly increasing due to the growing number and power requirement of processors, actuators, and accessories. However, drawing additional electric power from high pressure (HP) driven electric generators can limit the operation of the gas turbine engine, for example, by decreasing certain operating margins at peak demand.

The present disclosure includes descriptions of gas turbine engines that include low pressure (LP) motor-generators configured to supply of electric power. In certain adapted uses of the engines, for example, when adapted for use in an aircraft, the present disclosure includes devices, systems, and methods for integration of low pressure (LP) motor-generators into turbofan gas turbine engines. Motor-generators include devices that can be selectively operated in a first mode to generate electricity for use in other systems and in a second mode to drive mechanical rotation by consumption of electrical power. Coordinated operation of low pressure (LP) and/or high pressure (HP) motor-generators in response to various operational conditions promotes operational flexibility and power management optimization.

As shown in FIG. **1**, an illustrative turbofan gas turbine engine **10** includes a fan **12**, a compressor **14** having a compressor rotor **15**, a combustor **16**, and a turbine **18** having a high pressure (HP) turbine rotor **20** and a low pressure (LP) turbine rotor **22**, housed within a casing **24** as shown in FIG. **1**. The fan **12** draws air into the compressor **14** that compresses and delivers the air to the combustor **16**. The combustor **16** mixes fuel with the compressed air from the compressor **14** and combusts the mixture. The hot, high-pressure exhaust products of the combustion reaction in the combustor **16** are directed into the turbine **18** to cause rotation of the HP and LP turbine rotors **20**, **22** about an axis **25** to drive the compressor **14** and the fan **12**, respectively.

In the illustrative embodiment, the gas turbine engine **10** includes a high pressure (HP) spool **26** illustratively comprising the compressor rotor **15**, the HP turbine rotor **20**, and a high pressure (HP) drive shaft **28** that extends along the axis **25** to couple the compressor **14** for rotation with the HP turbine rotor **20**. In the illustrative embodiment, the gas turbine engine **10** includes a low pressure (LP) spool **30** illustratively comprising the fan **12**, the LP turbine rotor **22**, and a low pressure drive shaft **32** that extends along the axis **25** to couple the fan **12** for rotation with the LP turbine rotor **22**. In the illustrative embodiment, the drive shafts **28**, **32** are concentric shafts that extend along the axis **25** between forward **34** and aft ends **36** of the engine **10**.

In the illustrative embodiment as shown in FIG. **1**, the engine **10** includes a low pressure (LP) motor-generator **38** positioned between the fan **12** and the compressor **14** along the axis **25**. As shown in FIG. **2**, the LP motor-generator **38** illustratively includes a motor-generator core **40** having a stator **42** fixed against rotation relative to the LP drive shaft **32** and a rotor **44** coupled to the LP drive shaft **32** for rotation. The stator **42** is illustratively includes a number of stator windings **43** positioned radially outward of the rotor **44**, such that each is illustratively arranged in electromagnetic communication. In some embodiments, the motor-generator core **40** may include any suitable type and/or arrangement of electro-mechanical motor and/or generator. The LP motor-generator **38** is illustratively adapted for selective operation between a generation mode to generate electrical power from rotation of the LP turbine **22** and in a drive mode to receive electrical power for applying rotational force to the LP drive shaft **32**.

As shown in FIG. **2**, the LP drive shaft **32** illustratively includes a fan shaft **46** and a quill shaft **48** forming quill connections with each of the fan shaft **46** and a rotor hub **106** (on which the rotor **44** is illustratively mounted) to connect the rotor **44** for rotation with the fan shaft **46** while permitting relative movement therebetween. The quill shaft **48** illustratively includes a base **50** coupled to the fan shaft **46** and a flange **52** extending from the base **50** for connection with the rotor hub **106**. The rotor **44** of the LP motor generator **38** is illustratively mounted on the rotor hub **106**, which is supported by bearings **152**, **154** (as discussed below), while being connected for rotation with the LP drive shaft **32** through the quill shaft **48**. In some embodiments, a single quill connection may be used to rotationally connect the LP drive shaft **32** with the rotor **44** while permitting relative movement.

As best shown in FIGS. **3** and **6**, the LP motor generator **38** illustratively includes an electrical assembly **58** that electrically connects the LP motor-generator **38** to electrical loads of the engine **10**. The electrical assembly **58** illustratively includes a connector **62** attached to the LP motor-generator **38**, a set of three busbars **64** each having an end coupled with the connector **62**, and a terminal base **66** coupled to an opposite end of each of the busbars **64**. As shown in FIG. **6**, the busbars **64** illustratively extend radially outward from the LP motor generator **38** through a strut **56** of a support frame **54** of the engine **10** for connection with the terminal base **66** to communicate electric power to and from the LP motor-generator **38**.

As shown in FIGS. **7-14**, the turbofan gas turbine engine **10** illustratively includes a high pressure (HP) motor-generator **68**. The HP motor-generator **68** is illustratively embodied as being coupled to an auxiliary shaft **69** to receive driven rotation from the HP drive shaft **28**. The HP motor-generator **68** is illustratively adapted for selective operation in a generation mode to generate electrical power from rotation of the HP turbine rotor **20** or in a drive mode to receive electrical power to assist rotation of the HP drive shaft **28**.

In the illustrative embodiment, the turbofan gas turbine engine **10** includes a power control module **70** for governing electric power distribution within the engine **10**. The power control module **70** is illustratively electrically connected to each of the LP motor-generator **38** and HP motor-generator **68**. The power control module **70** is adapted to selectively receive and distribute electric power between the LP and HP motor-generators **38**, **68**, electric power users **72** (such as an airframe of a vehicle (aircraft) in adapted use of the engine **10**), and an energy storage device **74** (such as a battery), according to operational conditions of the engine **10** (and/or the vehicle).

As explained in detail below, the power control module **70** governs electric power management based on the operational conditions of the engine **10**. Under some conditions, the power control module **70** can direct electric power to the HP motor-generator **68** to assist rotation of the HP drive shaft **28** and/or reduce load on the HP turbine rotor **20**. Under some conditions, the power control module **70** directs electric power to the LP motor-generator **38** to assist rotation of the LP drive shaft **32** and/or reduce load on the LP turbine rotor **22**. Under some conditions, the power control module **70** communicates electrical power between one or both of the motor-generators **38**, **68** and the energy storage device **74**, and/or from any of the motor-generators **38**, **68** and the energy storage device **74** to electric power users **72**. As shown in FIG. **13**, the power control module **70** can be electrically connected to a second engine **111** to govern electric power management between engines **10**, **111**.

Returning now to FIGS. **1** and **2**, the fan **12** is illustratively disposed at the forward end **34** of the engine **10**. The fan **12** is illustratively attached to a fan shaft **46** of the LP drive shaft **32** for rotation about axis **25**. The fan **12** illustratively includes a fan rotor **76** and fan blades **78** that extend radially from the fan rotor **76**. The fan rotor **76** illustratively rotates the fan blades **78** about axis **25** to direct air axially into the engine **10**.

In the illustrative embodiment as shown in FIG. **2**, the fan shaft **46** of the LP drive shaft **32** is embodied as a hollow shaft that extends through the LP motor-generator **38** for connection with the fan rotor **76**. The fan shaft **46** is illustratively configured for splined connection with the LP drive shaft **32**, but in some embodiments may be integral with the LP drive shaft **32**. The fan shaft **46** of the LP drive shaft **32** receives driven rotation from the LP turbine rotor **22**.

As shown in FIG. **2**, the fan shaft **46** illustratively includes a first section **80** having an outer diameter, a tapered section **82** that extends from the first section **80** along the direction of the axis **25** towards the forward end **34**, and a hub **84** extending from the tapered section **82** along the axis **25** for connection with the fan **12**.

In the illustrative embodiment, the first section **80** of the fan shaft **46** is illustratively coupled with the LP turbine rotor **22** to receive driven rotation. The first section **80** illustratively includes an outer surface **86** having splines **88** that each extend along the direction of the axis **25** and have a radial height for connection with the quill shaft **48** (also shown in FIG. **3**). The outer surface **86** aftward of the splines **88** illustratively contacts a shaft bearing **92** to provide rotational support to the fan shaft **46**.

As shown in FIG. **2**, the first section **80** is illustratively positioned to extend axially though the LP motor-generator **38** to connect with the tapered section **82**. The tapered section **82** illustratively includes a tapered outer diameter that increases in size along the axial direction moving towards the forward end **34**. The tapered section **82** is illustratively positioned to extend axially through the LP motor-generator **38** to connect with the hub **84**.

As shown in FIG. **2**, the hub **84** illustratively includes a tiered section **90** adapted for contact with a shaft bearing **93** to support the LP drive shaft **32** for rotation within the engine **10**. Each of the shaft bearings **92**, **93** are illustratively arranged to receive lubricant from a lubricant distribution system **94** of the engine **10**. The tiered section **90** illustratively includes a constant outer diameter that contacts a shaft bearing **93** to reduce friction of the fan shaft **46** during rotation.

As shown in FIG. **2**, the fan shaft **46** is coupled with the quill shaft **48** for rotation. The quill shaft **48** is illustratively embodied as a hollow coupler forming a quill connection with the fan shaft **46** and the rotor hub **106** on which the rotor **44** is mounted. The base **50** of the quill shaft **48** illustratively includes a hollow cylinder **96** having an inner surface **98** and splines **100** that each extend along the direction of the axis **25** and have a radial height (also shown in FIG. **4**). The splines **100** of the quill shaft **48** are illustratively arranged complimentary to the splines **88** of the first section **80** of the fan shaft **46** to form the quill connection to allow relative movement between the fan shaft **46** and the quill shaft **48** while providing rotational coupling therebetween. The quill connection provides an offset from the fan shaft **46** to accommodate non-concentric rotation of the fan shaft **46** during a fan imbalance and/or blade off event, and/or axial misalignment therebetween.

The quill shaft **48** illustratively includes the flange **52** that extends radially outward from the base **50** for rotational connection with the LP motor-generator **38**. The flange **52** illustratively includes a neck **102** extending radially from the base **50** and a stem **104** connected to the neck **102** and partitioned radially spaced apart from the base **50**. The stem **104** illustratively forms another quill connection to the rotor hub **106** of the LP motor generator **38** that supports the rotor **44** for rotation with the LP drive shaft **32**. The stem **104** illustratively includes splines **105** formed on an outer surface thereof and complimentary to splines **107** form on an inner surface of the rotor hub **106** to form the quill connection to allow relative movement between the rotor hub **106** and the quill shaft **48** while providing rotational coupling therebetween.

Referring to FIG. **3**, the LP motor-generator **38** illustratively includes a housing **108** having a receptacle **110** and a cover **112** attached to the receptacle **110** and together defining an interior cavity **114** (as shown in FIG. **2**) for receiving the motor-generator core **40**. As best shown in FIG. **2**, the receptacle **110** illustratively includes an annular shell **116** extending along the direction of the axis **25** between a forward end **118** and an aft end **120**, a mount flange **122** attached to the aft end **120** of the annular shell **116**, and an overhang **124** attached to the forward end **118** of the annular shell **116**.

As best shown in FIG. **2**, the overhang **124** includes a limb **126** that extends radially inward from the forward end **118** of the annular shell **116** and an extension **128** connected to a radially inward end **130** of the limb **126**. The extension **128** illustratively extends from the limb **126** parallel to the axis **25** towards the aft end **120** spaced apart from the annular shell **116** by the radial length of the limb **126** to define a portion of the interior cavity **114**. The mount flange **122** is illustratively embodied as an annular flange extending perpendicularly to the axis **25** to receive connection of the cover **112**.

The cover **112** illustratively includes a cover flange **132** for connection to the mount flange **122** of the receptacle **110**, an annular section **134** extending from the cover flange **132** towards the aft end **36** of the engine **10**, and an overhang **136** extending from the annular section **134**. In the illustrative embodiment, the annular section **134** has a tapered outer

diameter increasing in size move towards the forward end **34** along the axis **25**. The overhang **136** of the cover **112** illustratively includes a limb **138** extending radially inward from the aft end of the annular section **134** and an extension **140** connected to the radially inward end **142** of the limb **138**. The extension **140** illustratively extends from the limb **138** parallel to the axis **25** towards the cover flange **132** spaced apart from the annular section **134** to define a portion of the interior cavity **114** of the housing **108**.

In the illustrative embodiment as shown in FIG. **2**, the extensions **128**, **140** are radially aligned and define a gap **142** axially therebetween. When the motor-generator core **40** is received within the interior cavity **114**, the rotor **44** is illustratively positioned within the gap **142** in electromagnetic communication with the stator **42**. The extensions **128**, **140** each respectively include an inner surface **144**, **146** and an outer surface **148**, **150** adapted to support a respective bearing **152**, **154** of the LP motor-generator **38**.

The bearings **152**, **154** are each illustratively embodied as a roller ball bearing having an outer race **156** that contacts the inner surface **144**, **146** of the respective extension **128**, **140** and an inner race **158** that contacts an outer surface **160** of the inner shaft **106** on which the rotor **44** is mounted. In the illustrative embodiment, the rotor **44** is coupled to the inner shaft **106** at a position between the bearings **152**, **154** for rotation with the fan shaft **46**.

As shown in FIG. **2**, the turbofan gas turbine engine **10** illustratively includes the lubricant distribution system **94** embodied as lubricant conduits formed within portions of the casing **24** for communicating lubricant, such as oil, to the bearings **92**, **93**, **152**, **154** and the stator **42**. In the illustrative embodiment, the housing **108** of the LP motor-generator **38** includes lubrication pathways **162** defined therein. The lubrication pathways **162** illustratively extend radially through the annular shell **116** to provide communication of lubricant from the lubricant distribution system **94** to the stator **42**.

As shown in the illustrative embodiment of FIG. **3**, the electrical assembly **58** is electrically connected to the LP motor-generator **38** to provide three electrically isolated busses for 3-phase power communication. In some embodiments, the electrical assembly **58** may be configured to communicate any suitable number of phase power. The connector **62** of the electrical assembly **58** is illustratively attached to the cover **112** at an aft side **164** of the LP motor-generator **38**. The connector **62** includes a mount **166** connected to the cover **112** and a body **168** that extends from the mount **166** to connect with the busbars **64**.

In the illustrative embodiment, the mount **166** extends generally for a length between opposite ends **170**, **172** thereof and includes a mount hole **174** defined therethrough on each end **170**, **172** to receive a fastener for connection to the cover **112**. The mount **166** is illustratively arranged generally tangential to the annular section **134**. The body **168** illustratively extends from the mount **166** at a position between the ends **170**, **172** and in a direction perpendicular to the length of the mount **166**. The body **168** illustratively includes a side **176** facing radially outward from the axis **25** having three recesses **176** defined therein for connection with one of the busbars **64**.

As best show in FIGS. **2** and **6**, the connector **62** illustratively includes three electrical connections **178** each comprising a socket **180** disposed within the body **168** and wires **182** connected to the socket **180**. Each socket **180** is illustratively embodied as a receptacle formed of conductive material and including interior threads **183** complimentary to exterior threads **184** of the busbars **64** to form a threaded connection between the connector **62** and the busbars **64**. In some embodiments, the connector **62** may include a floating connection with the busbars **64** to allow thermal movement therebetween while maintaining electrical connection.

In the illustrative embodiment as shown in FIG. **2**, each of the wires **182** is illustratively attached to one of the sockets **180** and is isolated from the other wires **182**. The wires **182** each illustratively extend through the body **168** and the mount **166** for connection with the stator **42** of the LP motor-generator **38**. The busbars **64** are illustratively electrically connected to the LP motor-generator **38** via the electrical connections **178**.

Referring now to the illustrative embodiment as shown in FIGS. **5** and **6**, the LP motor-generator **38** is positioned forward of the support frame **54** of the engine **10** along the axis **25**. The support frame **54** illustratively includes a hub **186** surrounding the axis **25** for receiving the LP motor-generator **38**, a collar **188** arranged radially outward of the hub **186**, and the strut **56** extending radially between the hub **186** and the collar **188**.

As shown in FIG. **6**, the hub **186** illustratively defines an interior space **190** therethrough to receive the aft end of the LP motor-generator **38**. The LP drive shaft **32** penetrates through the interior space **190** of the hub **186** for connection with the LP motor-generator **38**. The strut **56** illustratively connects with the hub **186** at an angular position of the connector **62** relative to the axis **25** that is complimentary, and illustratively equal, to the angular position about the axis **25**.

As best shown in FIG. **5**, the strut **56** illustratively includes a smooth outer surface **192** to minimize flow resistance. The strut **56** illustratively includes an interior cavity **194** defined therein that extends radially between the hub **186** and the collar **188**. The interior cavity **194** illustratively receives the busbars **64** therethrough to extend between the connector **62** and the terminal base **66**. Positioning the busbars **64** within the strut **56** provides physical protection while permitting conductive cooling of the busbars **64** by air passed over the strut **56**.

In the illustrative embodiment, the busbars **64** are each embodied as a rod formed of electrically conductive material, for example, copper. The busbars **64** each illustratively include the exterior threads **184** disposed on one end for fixed connection to one of the connector **62** and the terminal base **66**, and a cylindrical shape on the opposite end to slidably connect with the other of the connector **62** and the terminal base **66** to form a floating connection to accommodate thermal expansion. The busbars **64** are illustratively embodied to be secured within the interior cavity **194** surrounded with potting compound **196** to electrically isolate the busbars **64** from each other. The busbars **64** illustratively extend radially between the connector **62** and the terminal base **66** at an angle relative to a plane that is perpendicular to the axis **25**.

As best shown in FIG. **6**, the terminal base **66** is illustratively attached to the collar **188** at a position spaced apart from the connector along the axis **25**. The terminal base **66** illustratively includes a body **198** having three slots **200** defined radially therethrough each including a terminal socket **202** arranged therein to slidably receive one of the busbars **64** therein for electrical connection. The terminal sockets **202** are each illustratively embodied to include a hollow cylinder section **204** disposed within the body **198** and a stem **206** extending from the hollow cylinder section **204** radially outside of the body **198** as a terminal post for connection to electrical loads of the engine **10**. The terminal sockets **202** are illustratively formed of electrically conductive material to communicate electric power between the LP motor-generator **38** and electrical loads of the engine **10**. In some embodiments, the busbars **64** may be fixedly connected to the terminal base **66** and have a floating connection with the connector **62**.

Referring now to the illustrative embodiments of FIGS. **7-14**, the gas turbine engine **10** includes the power control module **70** that is electrically connected to each of the LP motor-generator **38** and HP motor-generator **68**. As mentioned above, the power control module **70** governs electric power management of the engine **10** based on the operational conditions of the engine **10**.

The power control module **70** is illustratively embodied as a main control unit including a processor **208**, a memory device **210** that stores instructions for execution by the processor **208**, communications circuitry **212** adapted to communicate signals with various components of engine **10** as directed by the processor **208**, and power distribution circuitry **214** adapted to communicate electric power with any of the motor-generators **38**, **68**, power users **72**, and the energy storage device **74** as directed by the processor **208**. The power control module **70** determines operational conditions of the engine based on signals received from various engine components and selectively operates the LP and HP motor-generators **38**, **68** based on the determined operational conditions.

In the illustrative embodiment as shown in FIG. **7**, the power control module **70** determines that the current operational conditions are steady state conditions. The steady state conditions illustratively include operational conditions in which the loads on the HP spool and the LP spool are within normal operating ranges such that no electrically-driven force of rotation on the drive shafts **28**, **32** is provided. Examples of such steady state conditions when the turbofan gas turbine engine **10** is adapted for use in an aircraft include ground idle, flight idle conditions, and/or flight cruise conditions.

In the illustrative embodiment, in response to steady state conditions, the power control module **70** is configured to operate the LP motor-generator **38** in the generation mode. The power control module **70** illustratively directs electric power generated by the LP motor-generator **38** to the power users **72** and selectively communicates electric power with the energy storage device **74**. The power control module **70** is illustratively embodied to selectively communicate electric power with the energy storage device **74** based on the operational conditions and the power storage levels of the energy storage device **74**.

In the illustrative embodiment as shown in FIG. **8**, the power control module **70** determines that the current operational conditions include low efficiency conditions. Low efficiency conditions include efficiencies of either of the HP spool **26** or LP spool **30** that are less than respective predetermined threshold efficiencies. In the illustrative embodiment, the efficiency of the HP spool **26** includes a fuel efficiency of the HP spool **26** as represented by an operating point of the compressor **14** along an operating curve as reflected on a plot of pressure ratio versus corrected flow.

In the illustrative embodiment, in response to determination of low efficiency conditions, the power control module **70** can selectively direct electric power generated from the LP motor-generator **38** in the generator mode to the HP motor-generator **68** in the drive mode to adjust the operating point of the compressor **14** along the operating curve to improve fuel efficiency of the HP spool **26**. In the illustrative embodiment, the power control module **70** can selectively direct electric power generated from the HP motor-generator **68** in the generator mode to the LP motor-generator **38** in the drive mode to adjust the operating point of the compressor **14** along the operating curve to improve fuel efficiency of the HP spool **26**. Thus, the power control module can selectively adjust the operating point of the compressor **14** along the its operating curve to improve engine fuel efficiency. In some embodiments, such low efficiency conditions when the turbofan gas turbine engine **10** is adapted for use in an aircraft include conditions in which any of the fuel efficiency and/or heat rate are less than a predetermined fuel efficiency and/or predetermined heat rate for either of the HP spool **26** or the LP spool **30**.

In the illustrative embodiment as shown in FIG. **9**, the power control module **70** determines that the operational conditions include high demand operational conditions. The high demand operational conditions illustratively include low compressor surge margin conditions and/or disruption of rotation of the fan **12**. Low compressor surge margin illustratively includes the amount of operating margin between the current compressor operating conditions and compressor surge conditions being below a predetermined threshold value. Examples of such high demand operational conditions when the turbofan gas turbine engine **10** is adapted for use in an aircraft include high altitude flight, fan **12** disruption events (e.g., fan rotor and/or blade damage from ice, birds, debris, etc.).

In the illustrative embodiment, in response to high demand operational conditions, the power control module **70** is configured to operate the LP motor-generator **38** in the generation mode and to direct electric power to the HP motor-generator **68** in the drive mode. For example, when the high demand operational conditions exist due to low compressor surge margin, the power control module **70** illustratively reduces the load on the HP Spool **26** by assisting rotation of the HP drive shaft **32** with the LP motor generator **38**, and increasing the operating margin between the current compressor operating conditions and compressor surge conditions.

In the illustrative embodiment as shown in FIG. **10**, the power control module **70** determines that the operational conditions include hot restart. When the engine **10** is adapted for use in an aircraft, hot restart operational conditions include in-flight restart conditions. Under such in-flight restart conditions, some ram air flow is illustratively received by the fan **12** because the aircraft is currently in flight. In response to hot restart operational conditions, the power control module **70** is illustratively configured to operate the LP motor-generator **38** in the generation mode and to direct electric power to the HP motor-generator **68** in the drive mode to assist restart of the engine **10**. The power control module **70** illustratively directs electric power from the power storage device **74** to the HP motor-generator **68**.

In the illustrative embodiment as shown in FIG. **11**, the power control module **70** determines that the operational conditions include loss of engine power. Loss of engine power illustratively includes an operational shut down of the engine **10**, where operational shut down includes elective shut down and unexpected shut down. In response to determination of loss of engine power operational conditions, the power control module **70** is configured to selectively operate the LP motor-generator **38** in the drive mode to selectively rotate the LP spool **30** to provide thrust assist. The power control module **70** illustratively directs electric power from the power storage device **74** to the LP motor-generator **38**. When the engine **10** is adapted for use in an aircraft, thrust assist can provide light and/or pulse thrust for additional stability control, navigational control, range extension, and/or landing assist.

In the illustrative embodiment as shown in FIG. **12**, the power control module **70** determines that operational conditions include hot engine off conditions. Hot engine off conditions illustratively include engine **10** being electively shut down while an operating temperature remains above a threshold temperature. In the illustrative embodiment, the operating temperature includes a lubricant temperature. In response to determination of hot engine off conditions, the power control module **70** operates the LP motor-generator in the drive mode to drive air through the engine **10**. Passing air through the engine **10** can cool engine components and can provide pressure to prevent accumulation of exhaust products into certain areas.

In the illustrative embodiment as shown in FIG. **13**, the power control module **70** is electrically connected with other turbo fan gas turbine engines **111**, illustratively three other engines **111**. Engines **111** are illustratively embodied as similar to engine **10** and each of the engines **10**, **111** are illustratively adapted for use in the aircraft. In some embodiments, the engines **111** may be any type of engine adapted for use in the aircraft and capable of generating electric power. The power control module **70** illustratively determines that electric high bypass conditions exist in engine **10**. Electric high bypass conditions illustratively include disengagement of engine **10** and one of the other engines **111** but with electrically driven rotation of their fans **12** to maintain high fan area.

In the illustrative embodiment, in response to determination of electric high bypass conditions, the power control module **70** operates the LP motor-generator **38** of the engines **10**, **111** in the drive mode to electrically drive rotation of their respective fans **12**. The power control module **70** illustratively directs electric power from any of the operating engines **111** and the energy storage device **74** to the disengaged engines **10**, **111**. Such selective electric high bypass operation promotes efficiency and flexibility across engines **10**, **111** and their platforms.

In the illustrative embodiment as shown in FIG. **14**, the power control module **70** operates the LP motor-generator **38** to inhibit rotation of the fan **12** while the engine **10** is powered off. The power control module **70** is illustratively connected to a stationary power source as indicated by ground power **113**. The power control module **70** illustratively directs power from the ground power **113** to the LP motor-generator **38** to inhibit rotation of the fan **12**. Such operation can prevent accidental rotation of the engine **10** components from natural wind which can be damaging without operation of the engine **10**.

In the illustrative embodiment, the power control module **70** determines the operational conditions based on signals received from various engine components. The various engine components illustratively include at least rotational speed sensors configured to detect the rotational speed of the LP and HP spools, compressor input and output pressure sensors adapted to determine inlet and outlet pressures of the compressor **14**. In some embodiments, the various engine components may include any of compressor surge margin sensors adapted to detect the amount of operating margin between the current compressor operating pressure and a compressor surge pressure, fuel rate sensors, and/or efficiency sensors (including at least temperature and pressure sensors for determining differentials across the LP turbine rotor **20** and HP turbine rotor **22**) adapted to determine operating efficiency of the HP spool **26** and LP spool **30**. In some embodiment, the engine **10** may include any number and/or arrangement of sensors for detecting and/or determining current operational parameters. In some embodiment, the 3-phase power arrangement may be used to determine LP shaft **32** speed indirectly.

In another illustrative embodiment as shown in FIG. **15**, the gas turbine engine **10** includes low pressure (LP) motor-generator **1038** having a motor-generator core **1040** configured for selective operation between a generation mode to generate electrical power from rotation of the LP turbine **22** and in a drive mode to receive electrical power for applying rotational force to a LP drive shaft **1032**. The LP motor-generator **1038** is similar to the LP motor-generator **38** as disclosed herein. Accordingly, similar reference numbers in the 1000 series indicate features that are common between the LP motor-generator **1038** and the LP motor-generator **38** unless indicated otherwise. The description of the LP motor-generator **38** is hereby incorporated by reference to apply to the LP motor-generator **1038** except in instances of conflict with the specific disclosure of the LP motor-generator **1038**.

The LP drive shaft **1032** illustratively includes a fan shaft **1046** including a generator mount **1048** that extends radially from the fan shaft **1046** to support the motor-generator core **1040**. In the illustrative embodiment, the motor-generator mount **1048** is fixedly connected with the fan shaft **1046** both in rotation and radial movement. The motor-generator core **1040** illustratively includes a stator **1042** and a permanent magnet rotor **1044** that can operate in electromagnetic communication with the stator **1042** with radial spacing **1045** between the rotor **1044** and the stator **1042**.

Unlike the LP motor-generator **38**, the LP motor-generator **1038** does not include bearings **152**, **154** independent from the shaft bearings **92**, **93**. Upon degradation and/or failure of any of the shaft bearings **92**, **93** such that the fan shaft **1046** does not rotate concentrically with the axis **25** such that the radial spacing **1045** is relatively large, the LP motor-generator **1038** is adapted to continue to support operation despite the increase in radial spacing **1045**.

In some embodiments, the motor-generators disclosed herein may be configured for operation in only one of a power mode and/or a generator mode.

While the disclosure has been illustrated and described in detail in the foregoing drawings and description, the same is to be considered as exemplary and not restrictive in character, it being understood that only illustrative embodiments thereof have been shown and described and that all changes and modifications that come within the spirit of the disclosure are desired to be protected.

What is claimed is:

1. A system of turbofan gas turbine engines, each of the turbofan gas turbine engines comprises

a low pressure spool including a fan rotor, a low pressure turbine rotor, a low pressure drive shaft extending along an axis and rotationally coupling the fan rotor to receive driven rotation about the axis from the low pressure turbine rotor, and a low pressure motor-generator mounted on the low pressure drive shaft and adapted for selective operation between a generation mode to generate electric power from driven rotation of the low pressure turbine rotor and a drive mode to electrically drive rotation of the low pressure drive shaft, and

a high pressure spool including a compressor rotor, a high pressure turbine rotor, a high pressure drive shaft extending along the axis and rotationally coupling the compressor rotor to receive driven rotation about the axis from the high pressure turbine rotor, and a high pressure motor-generator adapted for selective operation between a generation mode to generate electric power from driven rotation of the high pressure turbine rotor and a drive mode to electrically drive rotation of the high pressure drive shaft,

wherein the system comprises a power control module including at least one processor for executing instructions stored on memory and an energy storage device electrically connected to the power control module to selectively communicate electric power with the power control module, the power control module electrically connected to each of the low pressure motor-generator and the high pressure motor-generator of the each of the turbofan gas turbine engines and configured to determine operational conditions of the each of the turbofan gas turbine engines and to selectively operate each of the low pressure motor-generators and the high pressure motor-generators in either of the generation mode and the drive mode based on the determined operational conditions of the corresponding turbofan gas turbine engine,

wherein the power control module is configured to selectively operate the low pressure motor-generator of a select one of the turbofan gas turbine engines in the drive mode to provide propulsion thrust assist in response to determination that the operational conditions include loss of engine power of the select one of the turbofan gas turbine engines,

wherein the power control module is configured to provide electrical power for operating the low pressure motor-generator of the select one of the turbofan gas turbine engines by operation of at least one of the low pressure motor-generator and the high pressure motor-generator of at least one other turbofan gas turbine engine in the generation mode,

wherein the power control module is configured to selectively store electric power from one of the low pressure motor-generator and the high pressure motor-generator in the energy storage device based on the determined operational conditions of the aircraft,

wherein the power control module is configured to determine that electric high bypass conditions exist in a select two turbofan gas turbine engines, the electric high bypass conditions comprising disengagement of the select two turbofan gas turbine engines,

wherein the power control module is configured to provide electrical power from the energy storage device for operating the low pressure motor-generator and the fan of each of the select two turbofan gas turbine engines in response to determination that the operational conditions include electric high bypass conditions, and

wherein each of the turbofan gas turbine engines is adapted for use in an aircraft, and the power control module is configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist restart of the select one of turbofan gas turbine engines in response to determination that the operational conditions include in-flight restart.

2. The turbofan gas turbine engine of claim **1**, wherein the power control module is configured to operate the low pressure motor-generator in the generation mode in response to determination that the operational conditions are steady state operational conditions.

3. The turbofan gas turbine engine of claim **1**, wherein the power control module is configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist rotation of the high pressure drive shaft in response to determination that the operational conditions include an efficiency of the high pressure spool that is below a predetermined threshold.

4. The turbofan gas turbine engine of claim **3**, wherein the predetermined threshold is a predetermined fuel efficiency of the high pressure spool.

5. The turbofan gas turbine engine of claim **3**, wherein the power control module is configured to operate the high pressure motor-generator in the generation mode and to operate the low pressure motor-generator in the drive mode to assist rotation of the low pressure drive shaft in response to determination that the operational conditions include an efficiency of the low pressure spool that is below a predetermined threshold.

6. The turbofan gas turbine engine of claim **1**, wherein the power control module is configured to operate the low pressure motor-generator in the generation mode and to operate the high pressure motor-generator in the drive mode to assist the rotation of the high pressure drive shaft in response to determination that the operational conditions are high demand operational conditions.

7. The turbofan gas turbine engine of claim **6**, wherein high demand operational conditions include determination that a compressor surge margin is below a predetermined threshold value.

8. The turbofan gas turbine engine of claim **6**, wherein the turbofan gas turbine engine is adapted for use in an aircraft and high demand operational conditions include determination that a flight altitude is above a predetermined threshold value.

9. The turbofan gas turbine engine of claim **6**, wherein high demand operational conditions include determination of a disruption of rotation of the fan rotor.

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